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SPECIFICATION

A SPIN TRANSISTOR BASED ON THE SPIN-FILTER EFFECT, AND A NONVOLATILE ~~NON-VOLATILE~~ MEMORY USING SPIN TRANSISTORS

TECHNICAL FIELD

The present invention relates to a novel transistor. ~~More specifically, the present invention relates, and more particularly to a transistor having an~~ output characteristic depending characteristics of which depend on the direction of the spin of ~~carriers~~ a carrier, and to a nonvolatile memory circuit (nonvolatile memory) using ~~utilizing the same transistor.~~

BACKGROUND ART

~~As a~~ Conventionally, semiconductor memory used in electronic equipment typified by a microcomputer, a DRAM (Dynamic Random Access Memory) has been mainly used. Memories used in electronic devices such as microcomputers have mainly employed dynamic random access memories (DRAMs) from the viewpoint of operating speed and the degree of device integration. ~~In the DRAM, it is difficult to respond to a request to save energy and mobile equipment in recent years due to the problems that energy is consumed for holding memory and the stored contents are lost when turning off the power. To respond to such request, essential is a novel memory having a nonvolatile characteristic in addition to high speed, high integration and low power consumption characteristics.~~ It is difficult, however, for DRAMs to accommodate the recent demands for lower energy consumption and mobility because DRAMs consume energy for memory storage purposes and the stored data is lost once power supply is turned off. In order to address such demands, a novel memory is required that is nonvolatile as well as fast, highly integrated, and energy-saving.

~~Attention is being focused on an MRAM (Magnetoresistive Random Access Memory).~~ random access memories (MRAMs) are now gaining attention as a next-generation memory which can realize with the nonvolatile property, in addition to being capable of achieving operating speeds and levels of integration equal ~~comparable to those of the DRAM and has a nonvolatile characteristic.~~ DRAMs. The MRAM stores information according to the directions of magnetization of ferromagnetic substances and electrically reads the information according to the directions of magnetization ~~by~~ in terms of the direction of magnetization of a ferromagnet. The relative magnetization configuration of the information stored in the MRAM is electrically sensed utilizing the giant magnetoresistance effect of ~~in a spin valve device element,~~ or the tunneling magnetoresistance (TMR) effect of ~~in a magnetic tunnel junction (MTJ).~~ The MRAM which uses the ferromagnetic substances. Since MRAMs utilize a ferromagnet, they can hold information in a nonvolatile manner without consuming energy.

~~FIGS. 17(A) and 17(B) are diagrams showing~~ Fig. 17 shows a typical cell structure ~~configuration of an MRAM using an~~ utilizing a MTJ. As shown in ~~FIG~~ Fig. 17(A), in the MRAM, comprises a one 1-bit memory cell is constituted by ~~consisting of one MTJ and one metal oxide semiconductor (MOS (Metal Oxide Semiconductor) transistor.~~ The

gate of the MOS transistor is connected to a read word line wordline for sensing, the source thereof is grounded, and the drain thereof is connected to one end of the MTJ, and the other end of the MTJ is connected to a bit line bitline.

As shown in FIG. 17(B), the MTJ has a tunnel junction structure having a thin insulator film interposed between two ferromagnetic electrodes and has consisting of two ferromagnetic electrodes separated by a thin insulating film. The MTJ provides the TMR effect in which tunnel resistance is different according to the relative directions of magnetization of the two ferromagnetic electrodes. In particular, the rates of change of the TMR when the two ferromagnetic electrodes have parallel magnetization and when they have anti-parallel magnetization are called a TMR ratio which is used for evaluating the TMR effect.

The MRAM stores information by allowing the magnetization state of the MTJ, that is, the relative directions of magnetization of the two ferromagnetic electrodes to be parallel magnetization or anti-parallel magnetization by a synthesized magnetic field induced by electric currents flowed to a bit line and a rewrite word line, not shown, orthogonal thereto.

To read stored information stored in a specified varies depending on the relative magnetization configuration of the two ferromagnetic electrodes. The rate of change of TMR between the case where the two ferromagnetic electrodes carry parallel magnetization and the case where they carry antiparallel magnetization is referred to as the TMR ratio, which is used for the evaluation of the TMR effect.

In the MRAM, information is stored in terms of the configuration of magnetization of the MTJ. Specifically, the relative magnetization configuration of the two ferromagnetic electrodes is rendered either parallel or antiparallel using a composed magnetic field formed by magnetic fields induced by currents that are caused to flow through the bitline and a wordline for writing (not shown) disposed perpendicular to the bitline.

When sensing information stored in a particular cell, a voltage is applied to a specified read word line wordline for sensing connected to the cell to conduct so as to bring the MOS transistor, a read electric current (hereinafter, called a "driving current") is flowed from a specified bit line into conduction, so that a current for sensing (to be hereafter referred to as a "drive current") flows through the MTJ via a specific bitline connected to the cell to the MTJ, and the. A voltage dropped of across the MTJ based on due to the TMR effect is then detected as an output voltage to read sense the stored information.

DISCLOSURE SUMMARY OF THE INVENTION

The MRAM using the MTJ employs the ferromagnetic substances to have nonvolatile, low power consumption, and high speed characteristics. The Because the MRAMs based on MTJ employ ferromagnets, they are nonvolatile, energy-saving, and fast. In addition, their simple cell structure is simplified to be renders the MRAMs suitable for high density integration. The However, before the MRAM is expected can be realized as a next-generation nonvolatile memory. To realize this, there are, the following problems to must be solved overcome.

(1) The An MTJ has a binary exhibits two resistance values corresponding to the magnetization states of parallel magnetization and anti-parallel magnetization. The

~~MRAM flows the driving current to the MTJ to detect the resistance value parallel and antiparallel magnetization, and an MRAM detects these resistance values as an output voltage. To output voltages by causing a drive current to flow through the MTJ. Thus, in order to obtain a high output voltage, the thickness of the insulator film of the MTJ must be adjusted to optimize the tunnel resistance. tunnel resistance must be optimized by adjusting the thickness of the MTJ insulating film. However, since the TMR ratio also depends on the thickness of the insulator film, optimizing insulating film thickness, optimization of the tunnel resistance is limited.~~

~~(2) To precisely read the memory contents of information, the TMR ratio must be large to increase the ratio of the (2) Further, if the stored information is to be sensed accurately, the TMR ratio must be increased such that a high ratio of output voltages of the two magnetization states of configurations, i.e., parallel magnetization and anti-parallel magnetization. To realize a high TMR ratio, ferromagnetic substances having large spin polarizability must be used to optimize the forming method, material and film and antiparallel, can be obtained. In order to achieve a high TMR ratio, a ferromagnet with a large spin polarization must be employed, and also the method of forming an insulating layer and its material and thickness of the insulator layer, for example, must be optimized.~~

~~(3) In the an MRAM using the utilizing a MTJ, a the bias applied to the MTJ must be large increased in order to increase the operating speed. The However, the MTJ has an unavoidable the fundamental problem in principle that the TMR ratio is decreased when that, as the voltage drop caused between across the ferromagnetic electrodes is increased. The increases, the TMR ratio drops. Thus, the rate of change of an output voltage based on the TMR is decreased as the voltage drop caused in the MTJ is increased. The phenomenon is due to output voltages due to TMR decreases as the voltage applied to the MTJ increases. This phenomenon is inherently based on the TMR effect itself. It is difficult and hard to avoid it as long as the configuration of magnetization states are read only is sensed based solely on the TMR effect.~~

~~Summarizing the above problems Thus, in order to detect stored information stored in a MTJ with high sensitivity in the MTJ, the output voltages must be optimized by adjusting the impedance (junction resistance) of the MTJ must be adjusted to optimize the magnitude of output voltages. Further, the TMR ratio must be large. It is also necessary to increase the ratio of the output signals of signal ratio of the two magnetization states of configurations, namely, parallel magnetization and anti-parallel magnetization. The bias resistance of the TMR ratio is necessary so as not to decrease the TMR ratio by a bias and antiparallel, by increasing the TMR ratio. At the same time, the TMR ratio must be prevented from being lowered by biasing.~~

~~If an All of the aforementioned problems can be overcome if output signal characteristics can be freely designed by their terms of peripheral circuits other than a storage device circuitry regardless of the characteristic of the storage device, all the above problems can be solved characteristics of the memory elements.~~

~~An It is therefore an object of the present invention is to provide a nonvolatile memory in which stores information in ferromagnetic substances included is stored in terms of the magnetization configuration of a ferromagnet contained in a transistor according to a magnetization state and reads and in which the information is sensed using an the output~~

characteristics of the transistor ~~depending that depend~~ on the direction of the spin of ~~carriers the carrier~~.

~~According to~~ In one viewpoint of aspect, the present invention, ~~there is provided~~ provides a transistor ~~having comprising~~: a spin injector for injecting spin-polarized hot carriers by a spin -filter effect; and a spin analyzer for selecting the thus injected spin-polarized hot carriers by the spin -filter effect. ~~The~~ Thus, the output characteristics of the transistor can be controlled depending on the spin direction of the spin of the spin-polarized hot carriers.

~~Preferably, the~~ The spin injector has preferably comprises a first ferromagnetic barrier layer, a first nonmagnetic electrode layer joined to one end surface of the first ferromagnetic barrier layer, and a second nonmagnetic electrode layer joined to the other end surface of the first ferromagnetic barrier layer.

~~Preferably, the~~ The spin analyzer has preferably comprises: a second ferromagnetic barrier layer;; the second nonmagnetic electrode layer ~~joined to one end surface of the second ferromagnetic barrier layer;;~~ and a third nonmagnetic electrode layer joined to the other end surface of the second ferromagnetic barrier layer, ~~and shares the~~. The second nonmagnetic electrode layer with is joined to one end surface of the second ferromagnetic barrier layer. The second nonmagnetic electrode layer is common to the spin injector- and the spin analyzer.

~~Preferably, the~~ The first and second ferromagnetic barrier layers include preferably comprise an insulating ferromagnetic semiconductor or a ferromagnetic insulator, ~~and the~~. The energy band edges of these ferromagnetic barrier layers are constituted by any one of is preferably formed by an up -spin band and/or a down -spin band by the due to spin split. Preferably, the splitting. The thickness of the second nonmagnetic electrode layer is below preferably not greater than the mean free path of the spin- polarized hot carriers of in the second nonmagnetic electrode layer.

~~The~~ In the spin injector has a large tunnel, the tunneling probability to carriers having with respect to the carriers with a spin parallel to the spin band constituting forming the band edge of the first ferromagnetic barrier layer and a small tunnel probability to carriers having a spin anti-parallel thereto. The carriers having a spin parallel to the spin band constituting is large, whereas that with respect to the carriers with an antiparallel spin is small. Thus, carriers with a parallel spin with the spin band forming the band edge of the first ferromagnetic barrier layer can be injected as hot carriers from the first nonmagnetic electrode into the second nonmagnetic electrode layer as hot carriers.

~~The~~ On the other hand, the spin analyzer conducts, by, due to the spin -splitting at the band edge of the second ferromagnetic barrier layer, the spin- allows the spin-polarized hot carriers to be transported to the third nonmagnetic electrode layer when the spin direction of the spin- of the spin-polarized hot carriers injected into the second nonmagnetic electrode is parallel to the spin direction of the spin of the spin-band at the band edge of the second ferromagnetic barrier layer and. However, the spin analyzer does not conduct allow the spin-polarized hot carriers to be transported to the third ferromagnetic electrode when the spin direction of the spin-polarized hot carriers is anti-parallel to the direction of the spin antiparallel to that of the spin band at the band edge of the second ferromagnetic barrier layer.

~~The~~ Thus, even under the same bias condition, the output characteristics of the transistor under the same bias depends depend on the relative directions of magnetization of the first ferromagnetic barrier layer and the configuration of the first ferromagnetic barrier layer and second ferromagnetic barrier layer. When the first ferromagnetic barrier layer and the Specifically, the current transfer ratio or current gain is large when the first ferromagnetic barrier layer and second ferromagnetic barrier layer have parallel magnetization, a current transmission factor or a current amplification factor is high. When they have anti parallel magnetization, a current transmission factor or a current amplification factor is low, and it is small when they have antiparallel magnetization.

~~There is provided~~ The invention also provides a nonvolatile memory circuit in which stores information according to the relative directions of magnetization of the first ferromagnetic barrier layer and the second ferromagnetic barrier layer and reads the information based on the output characteristic of the transistor depending on the magnetization state. The memory circuit can constitute a memory cell by the transistor alone. information can be stored in terms of the relative magnetization configuration of the second ferromagnetic barrier layer and the first ferromagnetic barrier layer, and in which the information can be sensed using the output characteristics of the transistor that depend on the magnetization configuration. In this memory circuit, a memory cell can be configured with a single transistor.

~~According to another aspect of the present invention, there is provided a nonvolatile memory circuit having means storing information according to the directions of magnetization of ferromagnetic substances using a spin transistor including the ferromagnetic substances having an output characteristic depending on the direction of the spin of carriers, and means electrically reading the information stored in the spin transistor from the output characteristic.~~

In another aspect, the invention provides a nonvolatile memory circuit comprising a spin transistor containing a ferromagnet and having output characteristics that depend on the spin direction of the carriers, a means for storing information in terms of the relative magnetization configuration of the ferromagnet, and a means for electrically sensing information stored in the spin transistor using the output characteristics.

~~Preferably, the~~ The spin transistor has preferably comprises at least one ferromagnetic substance (hereinafter, called ferromagnet (to be hereafter referred to as a "free layer")) capable of independently controlling the direction of magnetization and at least one ferromagnetic substance (hereinafter, called a "pin layer") not changing the direction of magnetization, and holds, as stored information, in which the relative magnetization configuration can be independently controlled, and at least one ferromagnet in which the relative magnetization configuration is not changed (to be hereafter referred to as a "pin layer"). Stored information is retained in the form of a first state in which the direction of magnetization relative magnetization configuration of the free layer is the same as the direction of magnetization that of the pin layer and, or a second state in which the directions of magnetization their magnetization configurations are different.

Preferably, the spin transistor has comprises: a first electrode structure for injecting spin-polarized carriers; a second electrode structure for receiving the spin-polarized carriers; and a third electrode structure for controlling the quantity amount of the

spin-polarized carriers ~~conducted~~transported from the first electrode structure to the second electrode structure, ~~and the~~. The pin layer and the free layer are preferably included in any one of the first to third electrode structures.

~~There is provided a storage~~The invention also provides a memory circuit having a spin transistor arrayed comprising: the aforementioned spin transistors arranged in a matrix; a word line~~wordline~~ connected to the third electrode structures; a first wire~~grounding line~~ connecting the first electrode structure, ~~structures to ground;~~ and a bit line~~bitline~~ connected to the second electrode structure, ~~structures.~~ A plurality of word lines~~wordlines~~ are extended in the column direction. ~~Multiple bit lines, and a plurality of bitlines are extended in the direction crossing the same (the row direction);~~ perpendicular to the column direction. The spin transistors ~~is arrayed~~ are disposed near the ~~cross point~~intersections of the word line~~wordlines~~ and the bit line~~bitlines~~.

~~The~~In the aforementioned memory circuit, ~~inverts,~~ the magnetization ~~of~~in the free layer ~~by~~can be reversed by a magnetic fields ~~induced by flowing electric currents to a first another wire and a second another wire crossing in the state of being electrically insulated from each other on the spin transistor to change~~field induced by a current caused to flow through a first separate line and a second separate line intersecting one another above the spin transistor in an electrically insulated manner, whereby the relative magnetization state of configuration between the free layer and the pin layer for storing (or rewriting) information, can be changed so that information can be stored (or written).

~~— In place of the first another wire and the second another wire or any one of the first another wire and the second another wire, the word line and the bit line can be used or any one of the word line and the bit line can be used.~~

It is possible to use the wordline and/or the bitline instead of the first separate line and/or the second separate line.

~~The~~In the aforementioned memory circuit, ~~can read,~~ information ~~based on~~can be sensed using the output characteristics of the spin transistor when the free layer and the pin layer included in the spin transistor have parallel magnetization.

~~There is provided the~~The memory circuit in which ~~may comprise~~ an output terminal ~~is formed at~~on one end of each of the bit lines~~bitline~~, and a second wire~~line~~ branching~~ing~~ from each of the bit lines~~bitline~~ and connected ~~via a load to a power source~~ is provided, supply via a load.

In this case, the information can be read ~~by~~sensed from an output voltage obtained ~~based on~~from the voltage drop ~~of~~across the load ~~by an electric~~due to a current ~~produced between~~through the first and second electrode structures of the spin transistor, the output voltage depending on the relative magnetization state of configuration between the free layer and the pin layer.

Using the ~~above~~aforementioned circuit ~~can provide,~~ a high-integration density and high-speed nonvolatile memory circuit with high integration density ~~can be provided in which can design an~~ the output voltages ~~according to a~~ depending on the magnetization state in configuration within the transistor by ~~can be designed via the load and a power source~~supply.

BRIEF DESCRIPTION OF THE DRAWINGS

~~FIGS. 1(A) and 1(B) are diagrams showing~~Fig. 1 shows the structure of a spin - filter transistor according to this~~an~~ embodiment, in which FIG. 1(A) is of the invention. Fig. 1 (A) shows a schematic cross-sectional view and FIG. 1(B) is section. Fig. 1 (B) shows an energy band diagram of a conduction bands (or a valence bands) of the structure shown in FIG. 1(A)Fig. 1 (A), together with the directions of the spins of the spin bands of spin direction of a spin band in the barrier layers; layer.

~~FIGS. 2(A) and 2(B) are~~Fig. 2 shows an energy band diagrams when applying base-ground~~diagram in a case where a common-base bias voltages~~voltage is applied between the emitter (a first nonmagnetic electrode layer), the base (a second nonmagnetic electrode layer), and the ~~and~~ collector (a third nonmagnetic electrode layer) of the spin filter transistor according to this embodiment, in which FIG. 2(A) shows the case that the directions of magnetization of the first and second ferromagnetic barrier layers are parallel to each other and FIG. 2(B) shows the case that the directions of magnetization of the first and second ferromagnetic barrier layers are anti parallel to each other; ~~filter transistor of the present embodiment.~~ Fig. 2 (A) shows a case where the relative magnetization configuration of the first and second ferromagnetic barrier layers is parallel. Fig. 2 (B) shows a case where the relative magnetization configuration of the first and second ferromagnetic barrier layers is antiparallel.

~~FIGS. 3(A) and 3(B) are diagrams showing a static characteristic in the base ground of the spin filter transistor according to this embodiment in which the horizontal axis indicates collector base voltage V_{CB} in the right direction in the drawing~~Fig. 3 shows the static characteristics of the spin-filter transistor of the present embodiment in a common-base configuration. The horizontal axis shows collector-base voltage V_{CB} to the right and emitter-base voltage V_{EB} into the left direction therein and ~~that the top of the figure. The vertical axis indicates~~shows emitter current I_E , base current I_B , and collector current I_C ; in which FIG. 3(A) shows a characteristic of the case that the magnetization state. Fig. 3 (A) shows the characteristics in a case where the magnetization configuration between the ferromagnetic barrier layers of the emitter and the collector is parallel magnetization and FIG. 3(B) shows a characteristic of the case that it is anti-parallel magnetization; , while Fig. 3 (B) shows the characteristics in the case of antiparallel magnetization.

~~FIG. 4(A) is a diagram showing a structural example of memory cells using spin filter transistors 1 according to this embodiment, FIG. 4(B) is a diagram showing a structural example of a memory circuit, and FIG. 4(C) is a diagram in which the vertical axis indicates collector current I_C , the horizontal axis indicates collector-emitter voltage V_{CE} , and an I_C - V_{CE} characteristic of spin filter transistors 1 and a load straight line by a load resistance are shown in the same drawing;~~

~~FIG. 5(A) is a diagram schematically showing an example of an output characteristic of a current driven type spin transistor, and FIG. 5(B) is a diagram schematically showing an example of an output characteristic of a voltage driven type spin transistor;~~

~~FIG. 6(A) is a diagram showing a structural example of memory cells using voltage driven type spin transistors according to this embodiment, FIG. 6(B) is a diagram showing a structural example of a memory circuit, and FIG. 6(C) is a diagram in which the~~

~~vertical axis indicates drain current I_D , the horizontal axis indicates drain-source voltage V_{DS} , and an I_D - V_{DS} characteristic of voltage-driven type spin transistors 150 and a load curve by active load are shown in the same drawing;~~

Fig. 4 (A) shows an example of a memory cell utilizing a spin-filter transistor 1 of the present embodiment. Fig. 4 (B) shows an example of a memory circuit. The vertical axis of Fig. 4 (C) shows collector current I_C , and the horizontal axis shows collector-emitter voltage V_{CE} , together with the I_C - V_{CE} characteristics of the spin-filter transistor 1 and a load line due to a load resistor.

Fig. 5 (A) shows an example of the output characteristics of a current-driven spin transistor. Fig. 5 (B) schematically shows an example of the output characteristics of a voltage-driven spin transistor.

Fig. 6 (A) shows an example of a memory cell employing a voltage-driven spin transistor of the present embodiment. Fig. 6 (B) shows an example of a memory circuit. The vertical axis of Fig. 6 (C) shows drain current I_D , and the horizontal axis shows drain-source voltage V_{DS} , the figure also showing the I_D - V_{DS} characteristics of a voltage-driven spin transistor 150 and a load curve due to an active load in the same chart.

~~FIG. 7 is shows an energy band diagram showing a structural of an example of a hot-electron transistor type spin transistor;~~

~~FIG. 8 is shows an energy band diagram showing a structural of an example of a hot-electron transistor type spin transistor using heat-release employing thermionic emission injection;~~

~~FIG. 9 is shows an energy band diagram showing a structural of an example of a hot-electron transistor type spin transistor using utilizing the spin-filter effect;~~

~~FIG. 10 is shows an energy band diagram showing a structural of an example of a tunnel base transistor type spin transistor;~~

~~FIG. 11 is a cross-sectional view showing a structural example of a MOS transistor type spin transistor;~~

Fig. 11 shows a cross section of a MOS transistor type spin transistor.

~~FIG. 12 is shows a cross-sectional view showing a structural example section of a modulation-doped transistor type spin transistor;~~

~~FIG. 13 is shows a cross-sectional view showing a structural section of an example of a MOS transistor type spin transistor having comprising a ferromagnetic semiconductor channel;~~

~~FIG. 14 is shows a cross-sectional view showing a structural section of an example of a spin transistor having a structure in which a gate insulator film and a gate electrode are provided to comprising a ferromagnetic source, a ferromagnetic drain, and a nonmagnetic insulating tunnel barrier provided between a ferromagnetic source and a ferromagnetic drain; disposed between the source and the drain, wherein a gate insulating film and a gate electrode are formed on the tunnel barrier.~~

~~FIG. 15 is a cross-sectional view showing a structural example of a spin transistor having a structure in which a gate insulator film and a gate electrode are provided to an insulating ferromagnetic tunnel barrier provided between a ferromagnetic source and~~
Fig. 15 shows a cross section of an example of a spin transistor comprising a ferromagnetic source, a ferromagnetic drain or a nonmagnetic drain, and an insulating

ferromagnetic tunnel barrier disposed between the source and drain, wherein a gate insulating film and a gate electrode are formed on the tunnel barrier.

FIG. 16(A) is a diagram showing a structural example of memory cells having a shared source structure;

FIG. 16(B) is a diagram showing a cross sectional structure example of the memory cells having a shared source structure; and

Fig. 16 (A) shows an example of a memory cell with a common-source configuration.

Fig. 16 (B) shows a cross section of a memory cell with a common-source configuration.

FIG. 17 (A) is a diagram showing the structure of a typical conventional MRAM using an MTJ, and FIG. 17(B) is a diagram showing utilizing a MTJ. Fig. 17 (B) shows the operating principle of the MTJ.

BEST MODE FOR CARRYING OUT THE INVENTION The transistor according to the present invention comprises a spin injector for injecting spin-polarized hot carriers having the specific spin direction of a specified spin, and a spin analyzer, and a spin analyzer for selecting the thus injected spin-polarized hot carriers according to the direction of the spin-carries by their spin directions. The spin injector comprises a first ferromagnetic barrier layer having with such a thickness permitting a tunnel effect allowing for tunneling, such as Fowler-Nordheim tunnel or direct tunnel, a first nonmagnetic electrode layer joined to one end surface of the first ferromagnetic barrier layer, and a second nonmagnetic electrode layer tunneling or a direct tunneling; a first nonmagnetic electrode layer joined to one end surface of the first ferromagnetic barrier layer; and a second nonmagnetic electrode layer joined to the other end surface of the first ferromagnetic barrier layer. The spin analyzer comprises a second ferromagnetic barrier layer; a second nonmagnetic electrode layer joined to one end surface of the second ferromagnetic barrier layer; and a third nonmagnetic electrode layer joined to the other end surface of the second ferromagnetic barrier layer, and shares the second nonmagnetic electrode layer with the spin injector. The second nonmagnetic electrode layer is common to the spin analyzer and the spin injector. The thickness of the second nonmagnetic electrode layer is preferably below not greater than the mean free path of the spin-polarized hot carriers of in the nonmagnetic electrode layer.

The When the above-described structure is compared with the structure that of a known conventional hot electron transistor, The first nonmagnetic electrode layer and the first ferromagnetic barrier layer correspond to an the emitter and an emitter barrier. The emitter barrier, respectively; the second nonmagnetic electrode layer corresponds to a the base. The; and the second ferromagnetic barrier layer and the third nonmagnetic electrode layer correspond to a collector barrier and a collector the collector barrier and the collector, respectively.

The first and second ferromagnetic barrier layers include comprise an insulating ferromagnetic semiconductor or a ferromagnetic insulator. The energy bands of these ferromagnetic barrier layers are spin-split by magnetic exchange interaction. Only, and only an up-spin band or only a down-spin band exists at the band edges by the due to

this spin split-splitting. The energy width in which only one of the spin bands exists is called referred to as a spin split width.

~~According to the spin~~ The spin-filter effect of the spin injector takes advantage of the following fact. Namely, in the tunneling effect, such as Fowler–Nordheim (FN) tunneling or a direct tunnel produced by applying tunneling, in which a voltage is applied to the first ferromagnetic barrier layer via the first nonmagnetic electrode layer and the second nonmagnetic electrode layer to the first ferromagnetic barrier layer, large is the tunnel probability of the carriers having the direction of the spin (when the carriers are electrons, referring to the direction of the spin anti-parallel to the magnetization of the first ferromagnetic barrier layer, and when the carriers are holes, referring to the spin parallel to the magnetization of the first ferromagnetic barrier layer) matched with the direction of the spin, those of the carriers in the first nonmagnetic electrode layer that have a spin direction corresponding to that of the spin band at the band edge of the first ferromagnetic barrier layer (the spin direction being antiparallel to the magnetization of the first ferromagnetic barrier layer when the carriers are electrons, or parallel to the magnetization of the first ferromagnetic barrier layer when the carriers are hole) have a large tunneling probability, whereas those with a spin direction that does not correspond (the spin direction being parallel to the magnetization of the first ferromagnetic barrier layer of the carriers of the first nonmagnetic electrode layer, and small is the tunnel probability of the carriers having the direction of the spin (when the carriers are electrons, referring to the direction of the spin parallel to the magnetization of the first ferromagnetic barrier layer, and when the carriers are holes, referring to the spin anti-parallel to the magnetization of the first ferromagnetic barrier layer) not matched therewith when the carriers are electrons, or antiparallel to the first ferromagnetic barrier layer when the carriers are holes) have a small tunneling probability.

~~According to the~~ The spin-filter effect of the spin analyzer, in takes advantage of the ease effect that, when injecting spin-polarized hot carriers from the spin injector into the spin-split band of the second ferromagnetic barrier layer, when the direction of the spin of the injected spin-polarized hot carriers is parallel to the direction of the spin of the spin band at the band edge of the second ferromagnetic barrier layer (the first and second ferromagnetic barrier layers have parallel magnetization), the spin the spin-polarized hot carriers are conducted transported through the spin band of in the second ferromagnetic layer to and arrive at the third nonmagnetic electrode layer, and when the direction of the spin of the spin-polarized hot carriers is anti-parallel to the direction of the spin of the spin band at the band edge of the second ferromagnetic barrier layer (the first and second ferromagnetic barrier layers have anti-parallel magnetization), the spin- when the spin direction of the injected spin-polarized hot carriers is parallel to that of the spin band at the band edge of the second ferromagnetic barrier layer (where the first and second ferromagnetic barrier layers have parallel magnetization), whereas when the spin direction at the band edge of the second ferromagnetic barrier layer is antiparallel to that of the spin-polarized hot carriers (where the first and second ferromagnetic barrier layers have antiparallel magnetization), the spin-polarized hot carriers cannot be conducted transported through the second ferromagnetic barrier layer.

~~According to the above structure~~ In this arrangement, the carriers in the first

nonmagnetic electrode layer having with the spin direction of the spin parallel to the direction of the spin that of the spin band at the band edge of the first ferromagnetic barrier layer are injected as spin-polarized hot carriers into the second nonmagnetic electrode layer by the tunnel effect tunneling, such as Fowler-Nordheim tunneling or a direct tunnel. At this time, the above tunneling. The transistor is biased so such that the energy of the injected spin thus injected spin-polarized hot carriers is larger than the energy at of the spin band edge at the band edge of the second ferromagnetic barrier layer and is smaller than the energy in of the spin band edge to which the spin split width is applied to the spin band edge. The has been added. Since the thickness of the second nonmagnetic electrode layer is below not greater than the mean free path of the spin-polarized hot carriers in the second nonmagnetic electrode layer, the injected spin-polarized hot carriers reach arrive at the second ferromagnetic barrier layer without losing energy. The In addition, the energy of the spin-polarized hot carriers is larger than the energy that of the spin band edge at the band edge of the second ferromagnetic barrier layer and is smaller than the energy in of the spin band edge to which the spin-split width is added to the spin band edge. When the direction of the spin of the injected spin-split width has been added. Therefore, when the spin direction of the injected spin-polarized hot carriers is parallel to the direction of the spin spin direction of the spin band at the band edge of the second ferromagnetic barrier layer, the spin-polarized hot carriers are conducted through transported within the spin band by an electric field produced in the second ferromagnetic barrier layer, are carried and transported to the third nonmagnetic electrode layer, and become an electric producing a current flowing that flows between the third nonmagnetic electrode layer and the first nonmagnetic electrode layer.

When the direction of the spin On the other hand, when the spin direction of the injected spin-polarized hot carriers is anti-parallel antiparallel to the direction of the spin spin direction of the spin band at the band edge of the second ferromagnetic barrier layer, the spin-polarized hot carriers are scattered (or backscattered) at reflected by the interface of boundary between the second nonmagnetic electrode layer and the second ferromagnetic barrier layer, and become an electric producing a current flowing that flows between the second nonmagnetic electrode layer and the first nonmagnetic electrode layer.

Depending Thus, depending on whether the relative directions of magnetization configuration of the first ferromagnetic barrier layer and the second ferromagnetic barrier layer, namely, whether they are parallel or anti-parallel antiparallel, the electric current flowing that flows in the first ferromagnetic barrier layer can be switched to the electric current flowing via the second ferromagnetic barrier layer that flows between the third nonmagnetic electrode layer and the first nonmagnetic electrode layer or the electric current flowing via the same via the second ferromagnetic barrier layer, or a current that flows between the second nonmagnetic electrode layer and the first nonmagnetic electrode layer. The electric current flowing via Namely, the current through the second ferromagnetic barrier layer can be controlled according to by the relative directions of magnetization configuration of the first ferromagnetic barrier layer and the second ferromagnetic barrier layer. This corresponds to control of a collector current by a base current, as When compared with the operation of a known common-base or common-emitter hot electron transistor and bipolar transistor of a base ground or an emitter ground. The transistor

~~according to this embodiment can control the current amplification factor~~transistors or bipolar transistors, the above-described operation of the present embodiment corresponds to controlling the collector current by means of the base current. However, in the transistor of the present embodiment, the factor of amplification of the collector current by the base current according to~~can be controlled by the relative directions of magnetization configuration of the first ferromagnetic barrier layer and the second ferromagnetic barrier layer.~~The~~Thus, the transistor according to this of the present embodiment is a transistor capable of controlling the current amplification factor and can control the collector current according to the relative directions of gain, whereby collector current can be controlled not only by the base current (or the bias voltage between the first and second nonmagnetic electrodes), but also by the relative magnetization configuration of the first ferromagnetic barrier layer and the second ferromagnetic barrier layer as well as to the base current (or a bias voltage between the first and second nonmagnetic electrodes).~~

~~The coercivity of~~Furthermore, when the coercive forces of the first ferromagnetic barrier layer and the second ferromagnetic barrier layer is changed or one of the magnetization directions is fixed. A magnetic field having a suitable strength in which any one of the directions of magnetization are varied, or when the relative magnetization configuration of one of them is fixed, the relative magnetization configuration of the first ferromagnetic barrier layer and the second ferromagnetic barrier layer is inverted is applied to arbitrarily change the relative directions of magnetization of the first ferromagnetic barrier layer and the second ferromagnetic barrier layer to parallel or anti parallel. In other words can be changed to be parallel or antiparallel as desired by applying a magnetic field of an appropriate intensity such that the relative magnetization configuration of either the first ferromagnetic barrier layer or the second ferromagnetic barrier layer is reversed. Namely, information can be stored in the transistor.

~~A~~Thus, a memory cell can be constituted using with the above-described transistor. An example of a nonvolatile memory using~~utilizing the transistor according to this embodiment will be described below. The second nonmagnetic electrode layer of the transistor according to this of the present embodiment will be hereafter described. The second nonmagnetic electrode layer of the transistor of the embodiment is connected to a wordline-line, and~~The third nonmagnetic electrode layer of the transistor is connected to a bit line. The bit line is connected via a load to a power source to ground the first nonmagnetic electrode layer of the transistor. According to this structure, a specified word line is selected to apply to a power supply via a load, and the first nonmagnetic electrode layer of the transistor is grounded. In this arrangement, when a specific wordline is selected and a bias is applied to the second nonmagnetic electrode layer. A specified bit line is selected to detect an, the output voltage (a voltage produced that appears at the edge of the third nonmagnetic electrode). The output voltage is changed according to the relative directions of magnetization of the first ferromagnetic barrier layer and the second ferromagnetic barrier layer of the transistor. When the relative directions of magnetization detected by selecting a specific bitline is seen to vary depending on the relative magnetization configuration of the first ferromagnetic barrier layer and the second ferromagnetic barrier layer of the transistor. Namely, when the relative magnetization configuration are parallel, the output voltage is smaller. When the relative directions of

magnetization are anti-parallel, the output voltage is larger. Stored becomes smaller, while when the relative magnetization configuration is antiparallel, the output voltage becomes larger. Thus, the information that is stored can be read depending on the basis of the magnitude of the output voltage.

In the above-described nonvolatile memory, the transistor according to this of the present embodiment is used as an a common-emitter ground-transistor, the power source and supply and a load are added provided to the collector, and the collector voltage is an output voltage. An output voltage when the first obtained as the output voltage. Thus, using peripheral circuitry such as the power supply and load, desired output voltage values can be obtained when the first ferromagnetic barrier layer and second ferromagnetic barrier layers have parallel magnetization by the peripheral circuits as a source voltage and load and an output voltage or when they have anti-parallel antiparallel magnetization can be designed to desired values. Using. Accordingly, the above-described nonvolatile memory can solve the overcome the aforementioned problems of the MRAM based on MTJ, the problems being that the tunnel resistance is small and the output voltage is small in the MRAM using the MTJ as well as output voltages are small, that the TMR ratio is so small and stored that the information that is stored is hard to identify be distinguished, and that the ratio of the output voltages is smaller by decreases due to the applied bias.

The structure In the following, the configuration and operation of the above-described transistor will be described below in greater detail with reference made to the drawings. To easily understand the following description, the The transistor according to this of the present embodiment is called a spin will be hereafter referred to as a "spin-filter transistor" for facilitating the understanding of the description of the invention.

FIGS. 1(A) and 1(B) are diagrams showing the structure Fig. 1 shows the configuration of a spin -filter transistor according to this the present embodiment, in which FIG. 1(A) is. Fig. 1 (A) shows a schematic cross-sectional view and FIG. 1(B) is section. Fig. 1 (B) shows an energy band diagram of the conduction bands (or the valence bands) of the structure shown in FIG. 1(A) with the directions of the spins of the spin bands of barrier layers band) of the configuration shown in Fig. 1 (A), also showing the spin direction of the spin band in the barrier layer. When the carriers are holes, the direction of the spin magnetization at the band edge is matched with the direction of magnetization. When corresponds to the spin direction; when the carriers are electrons, the direction of the spin at the band edge is opposite the direction of magnetization. relative magnetization configuration is opposite to that of the spin direction of the band edge.

A spin -filter transistor 1 according to this the present embodiment has comprises a spin injector 5 having comprising: a first ferromagnetic barrier layer 2, 2; a first nonmagnetic electrode layer 3 joined to one end surface of the first ferromagnetic barrier layer 2, 2; and a second nonmagnetic electrode layer 4 joined to the other end surface of the first ferromagnetic barrier layer 2; and 2. The spin-filter transistor 1 also comprises a spin analyzer 8 having comprising: a second ferromagnetic barrier layer 6, the 6; a second nonmagnetic electrode layer 4 joined to one end surface of the second ferromagnetic barrier layer 6, and the 6; and a third nonmagnetic electrode layer 7 joined to the other end surface of the second ferromagnetic barrier layer 6. As is apparent will be seen from FIG Fig. 1 (A), the spin injector 5 and the spin analyzer 8 shares the second nonmagnetic electrode layer 4.

~~As the~~The first, second, and third nonmagnetic electrode layers 3, 4, and 7 may be formed by a nonmagnetic metal, an n-type nonmagnetic semiconductor, or a p-type nonmagnetic semiconductor can be used. Preferably, the thickness of the second nonmagnetic electrode layer 4 is below preferably not greater than the mean free path ~~in within~~ the nonmagnetic electrode layer 4 of the spin-polarized hot carriers injected from the spin injector. ~~The~~ By making the base width is shorter than the mean free path to allow a, the current transmission factor to be transfer ratio can be made 0.5 or above. ~~The greater,~~ so that current amplification function can be obtained. can be achieved.

~~As the~~The first and second ferromagnetic barrier layers 2 and 6 may comprise an insulating ferromagnetic semiconductor or a ferromagnetic insulator can be used. The energy band of the ferromagnetic barrier layer is spin split by magnetic exchange interaction. ~~An energy region in which, such that an energy region is created at the band edge where only an up-spin or only a down-spin exists can be formed at the band edge. The spin.~~ Such a spin-polarized band is called referred to as a spin band. The energy region width is called a spin-, and this energy region band is referred to as a spin-split width Δ .

As shown in FIG. 1 (B), the solid lines indicated by the arrows \uparrow ~~to with an arrow~~ \uparrow on the ferromagnetic barrier layers 2 and 6 denote indicate the edge of the band edges in which where an up spin can exist, that is, namely, an up spin band edges 9. The solid lines indicated by the arrows \downarrow ~~thereto denote~~ with an arrow \downarrow indicate the edge of the band edges in which where a down spin can exist, that is, namely, a down spin band edges 10. The portion region between the up spin band edge 9 and the down spin band edge 10 in FIG. 1 (B) is a region in which where only the an up spin can exist. A region having an energy with a higher energy than that of the down spin band edge 10 is a region in which where both the up spin and the down spin can exist. ~~FIG~~ While Fig. 1 (B) shows the a case that where the spin band of the up spin is lower than the spin band of the down spin, the reverse opposite state is also possible.

The first ferromagnetic barrier layer 2 has a thickness in which such that the carriers can be transmitted from the first nonmagnetic electrode layer 3 to the second nonmagnetic electrode layer 4 by the tunnel effect tunneling, such as Fowler-Nordheim tunnel (hereinafter, called an FN tunnel-Nordheim tunneling (to be hereafter referred to as "FN tunneling") or a direct tunnel by tunneling, in response to the application of a voltage applied to the first nonmagnetic electrode layer 3 and to the second nonmagnetic electrode layer 4. ~~The~~ A direct tunneling refers to the phenomenon in which the carriers are directly transmitted pass through a thin potential barrier. The FN tunneling refers to the phenomenon in which the tunneling current by the due to a direct tunneling can be neglected ignored up to a certain applied voltage and in which the carriers are tunneled tunnel through the triangular potential in at the upper portion top of a potential barrier produced by applying the application of a voltage above exceeding a certain value.

~~A~~The voltage applied to the first nonmagnetic electrode layer 3 and the second nonmagnetic electrode layer 4 may be in the voltage range used in a typical the conventional memory circuit, e.g., of such as on the order of some hundreds of several hundred mV to several V volts. The thickness of the second ferromagnetic barrier layer 6

~~must be a thickness so that thermal release needs to be sufficiently thick that there is no thermionic emission of the carriers and an electric current by the due to tunneling (the so-called leak current) do not occur from the second nonmagnetic electrode layer 4 to the third nonmagnetic electrode layer 7.~~

The nonmagnetic electrode layers 3, 4 and 7 and the ferromagnetic electrode layers 2 and 6 form the energy band structures shown in FIG. 1 (B). Solid lines 11 in the nonmagnetic electrode layer portions in FIG. 1 (B) show indicate the Fermi energy of a metal, the Fermi energy of an n-type (p-type) semiconductor, or the energy at the bottoms of the conduction bands (at the tops of the valence bands). The lower energy barriers of in the ferromagnetic barrier layers 2 and 6 corresponding to the solid lines 11 at the nonmagnetic electrode layer portions are indicated by ϕ_c and Δ , and the spin-split widths are indicated by Δ . Although the ferromagnetic barrier layers 2 and 6 may have different ϕ_c and Δ , the case that values of ϕ_c and Δ , the following description concerns a case where the ferromagnetic barrier layers 2 and 6 have the same ϕ_c values of ϕ_c and Δ will be shown below. When Δ .

In the case where the carriers are electrons, a nonmagnetic metal or an n-type semiconductor is used as for the nonmagnetic electrode layers 3, 4, and 7, and an insulating ferromagnetic semiconductor or a ferromagnetic insulator is used as for the ferromagnetic barrier layers 2 and 6. In this case, the up-spin band edges 9 and the down-spin band edges 10 are produced by the spin splitting of the bottom of the conduction band of the ferromagnetic barrier layers 2 and 6 are those in which the bottoms of the conduction bands are spin split. When Δ . In the case where the carriers are holes, a p-type semiconductor is used as for the nonmagnetic electrode layers 3, 4 and 7, and an insulating ferromagnetic semiconductor or a ferromagnetic insulator is used as for the ferromagnetic barrier layers 2 and 6. In this case, the up-spin band edges 9 and the down-spin band edges 10 of the ferromagnetic barrier layers 2 and 6 are those in which the tops produced by the spin splitting of the top of the valence bands are spin split band.

Hereafter, the operating principle of the above-described spin-filter transistor will be described in detail. In the following description, for simplifying the description, the notation of the notational system for the hot electron transistor is used together. The will also be used for simplicity's sake. Specifically, the first nonmagnetic electrode layer 3 and the first ferromagnetic barrier layer 2 are called will be referred to as an emitter 21. The second nonmagnetic electrode layer 4 is called will be referred to as a base 22. The second ferromagnetic barrier layer 6 and the third nonmagnetic electrode layer 7 are called will be referred to as a collector 23. The first nonmagnetic electrode layer 3 is called the will be referred to as an emitter electrode 3. The 3, and the third nonmagnetic electrode layer 7 is called the will be referred to as a collector electrode 7. An example of the case that The following also concerns the case where the carriers are electrons will be described (when as an example (the case where the carriers are holes, the will not be described because such a case is substantially the same in terms of operating principle is essentially the same and the description is omitted).

FIGS. 2(A) and 2(B) are shows energy band diagrams when applying base ground in a case where a common-base bias voltage is applied between the emitter,

the base, and the collector of the spin filter transistor according to this embodiment, in which FIG. 2(A) shows the case that the directions of the present embodiment. Fig. 2 (A) shows a case where the magnetization configurations of the first and second ferromagnetic barrier layers are parallel to each other and FIG. 2(B) shows the case that the directions of, and Fig. 2 (B) shows a case where the magnetization configurations of the first and second ferromagnetic barrier layers are anti-parallel to each other and corresponds to FIG. 2(A). Bias, corresponding to Fig. 2 (A). A bias voltage V_{EB} is applied between the across emitter 21 and the base 22. Bias 22, and a bias voltage V_{CB} is applied between the across base 22 and the collector 23. The magnitude of the V_{EB} is set to satisfy such that the relationship of $(\phi_C (\Phi_C < qV_{EB} < \phi_C \Phi_C + \Delta))$ is satisfied, where q is the elementary charge quantum.

The emitter 21 serves functions as a spin injector for injecting spin-polarized hot electrons into the base 22. When the bias voltage V_{EB} tunnel passes. Thus, when causing the carriers from the emitter electrode 3 to pass through the first ferromagnetic barrier layer 2, from the emitter electrode 3 by tunneling using the bias voltage V_{EB} , since the conduction band of the first ferromagnetic barrier layer 2 is spin-split and the barrier heights felt by an up-spin electron 24 and a down-spin electron 25 existing split, the barrier height for the up-spin electrode 24 and that for the down-spin electrode 25 in the emitter electrode 3 are different. In FIG. 2

Namely, in Fig. 2 (A), the barrier height felt by the up-spin electron 24 is an energy to the up for the up-spin electrode 24 corresponds to the energy up to an up-spin band edge 9 of the first ferromagnetic barrier layer 2, that is, ϕ_C or Φ_C . The barrier height felt by the down-spin electron 25 is an energy to the down for the down-spin electrode 25 corresponds to the energy up to a down-spin band edge 10 of the first ferromagnetic barrier layer 2, that is, $\phi_C + \Delta$. Control of $\Phi_C + \Delta$. Thus, by controlling the base-emitter voltage can selectively tunnel inject, as a hot electron, the electron having a spin having a lower felt barrier height, in this case, the electron 24 having an up-spin into the base 22 (this phenomenon is emitter voltage, electrons with a spin for which the barrier height is lower, namely, an up spin, which correspond to electrons 24 in the illustrated example, can be selectively tunnel-injected to the base 22 (in a phenomenon called the "spin filter effect") as hot electrons.

The collector 23 of the spin filter transistor serves functions as a spin analyzer for selecting the direction of the spin-polarized hot electrons injected into the base 22. A spin-polarized hot electron 26 which becomes hot. Specifically, the spin-polarized electrons 26 that have been rendered into hot electrons by the bias voltage V_{EB} and is injected into the base 22, since the width of the base 22 is set below the mean free path of the spin-polarized hot electron 26, can ballistically 22 can arrive at the interface of the boundary between base 22 and the collector 23 without losing energy, or "ballistically," because the width of base 22 is set to be not greater than the mean free path of the spin-polarized hot electrons 26. In the second ferromagnetic barrier layer 6 of the collector 23, there is also produced two barriers having with different barrier heights occur by due to the spin splitting of the conduction bands band. As shown in FIG. 2 (A), when the directions of magnetization configurations of the first and second ferromagnetic barrier

layers 2 and 6 are parallel to each other, because the up -spin band edge 9 of the second ferromagnetic barrier layer 6 having a spin parallel to that of the spin-polarized hot electron 26 has an energy lower than that of the spin-polarized hot electron 26. The spin-polarized hot electron 26 is conducted to cross over-polarized hot electrons 26 is lower than the energy of the spin-polarized hot electrons 26, the spin-polarized hot electrons 26 are transported to the collector electrode 7 across the second ferromagnetic barrier layer 6 to the collector electrode 7 to be 6, thereby producing a collector current I_C .

As shown in FIG. 2(B) On the other hand, when the directions of magnetization configurations of the first and second ferromagnetic barrier layers 2 and 6 are anti-parallel antiparallel to each other, as shown in Fig. 2 (B), spin-polarized hot electrons 27 having a with down spin is are injected into the to a base 22. The In this case, however, because the down -spin band edge 10 of the second ferromagnetic barrier layer 6 having a with down spin has an energy is higher than that the energy of the spin-polarized hot electrons-27. 27, The spin-polarized hot electrons 27 cannot be conducted transported through the conduction band of the second ferromagnetic barrier layer 6 and is subject 6. Instead, they lose energy as they are subjected to spin-dependent scattering (or backscattering reflection) at the interface of the boundary between base 22 and the collector 23 to lose energy to become 23, resulting in a flow of base current I_B .

The current transmission factor of an electric current flowing Thus, the current transfer ratio of the current that flows from the emitter to the collector is largely different greatly differs depending on the relative directions of magnetization configuration of the first ferromagnetic barrier layer 2 of the emitter 22 and the second ferromagnetic barrier layer 6 of the collector 23. In other words, the current amplification factor gain of the collector current by the due to base current is largely different greatly differs.

FIGS. 3(A) and 3(B) are diagrams showing a static characteristic in the base-ground Fig. 3 shows the static characteristics of the spin -filter transistor according to this of the present embodiment in which the a common-base configuration. The horizontal axis indicates shows collector-base voltage V_{CB} in the upper-right direction in the drawing portion and emitter-base voltage V_{EB} into the left direction therein and the. The vertical axis indicates shows emitter current I_E , the base current I_B , and collector current I_C ; in which FIG. 3(A) shows a static characteristic of the case that the directions of. Fig. 3 (A) shows the static characteristics in a case where the magnetization configurations of the ferromagnetic barrier layers of the emitter and the collector are parallel and FIG. 3(B) shows a static characteristic of the case that they are anti-parallel. In FIGS. Fig. 3 (B) shows the static characteristics when the magnetization configurations are antiparallel. In both Fig. 3 (A) and 3(B), α is a current transmission factor, β is a current amplification factor α indicates the current transfer ratio, β indicates the current gain, and the subscripts $\uparrow\uparrow\uparrow$ and $\downarrow\uparrow\uparrow$ indicate the case that the parallel and antiparallel relative directions of magnetization configuration, respectively, of the ferromagnetic barrier layers of the emitter and the collector are parallel and the case that they are anti-parallel.

As shown in FIG Fig. 3 (A), when the directions of magnetization configurations of the emitter and the collector are parallel, most of the emitter current I_E can be serve as the collector current I_C . As shown in FIG Fig. 3 (B), when the directions of

~~magnetization are anti-parallel magnetization configurations are antiparallel~~, most of the emitter current I_E can ~~be serve as~~ the base current I_B . ~~Like a~~ As in the known hot electron transistors or bipolar transistor, the transistor according to this embodiment can ~~control~~ transistors, the collector current I_C can be controlled by the base current I_B . It can ~~control the current amplification factor according to~~ in the transistor of the present embodiment. In addition, the current gain can be controlled by the relative directions of magnetization configuration of the first and second ferromagnetic barrier layers.

~~As the~~The ferromagnetic barrier layer of the spin filter transistor according to ~~this of the present embodiment~~, may comprise a ferromagnetic semiconductor, such as EuS, EuSe, and EuO ~~can be used~~. A or EuO, for example. It may also comprise a ferromagnetic insulator, such as $R_3Fe_5O_{12}$ (where R expresses ~~is~~ a rare-earth element) ~~can be also used~~. As a. The nonmagnetic electrode layer, ~~a~~ may comprise any material as long as it is nonmagnetic substance ~~may be used~~. For instance, a metal. Examples include metals, such as Al ~~or~~ and Au, ~~or a~~ and nonmagnetic semiconductor ~~semiconductors~~, such as Si ~~or~~ GaAs which is impurity ~~and~~ GaAs, that have been doped with a high density ~~may be used~~. When EuS is used as a concentration of impurity. When, for example, the ferromagnetic barrier layer and Al is used as ~~a~~ comprises EuS and the nonmagnetic electrode layer comprises Al, the barrier height $\hat{\phi}_c = \phi_c$ is 1.4eV and the spin-split width $\Delta = \Delta$ is 0.36eV. The spin filter transistor according to ~~this of the present~~ embodiment can be manufactured using the above material ~~produced~~ by a known method, such as molecular beam epitaxial growth ~~method~~ epitaxy, vacuum deposition method ~~and~~ evaporation, or sputtering method, using the above-described materials.

~~A~~In the following, a nonvolatile memory using ~~comprising~~ the spin filter transistor of the present invention as a memory cell will be described.

~~FIG. 4(A) is a diagram showing a structural~~Fig. 4 (A) shows an example of a memory cell using ~~the~~employing a spin filter transistor 1 according to ~~this of the present~~ embodiment. In the memory cell shown in ~~FIG~~Fig. 4 (A), a number of spin filter transistors are arranged in a matrix, ~~with the emitter terminals E is grounded to connect and the collector terminals C and base terminal B to read bit line BL and read word line WL. A rewrite word line and a rewrite bit line are arranged to cross each other on the base terminals B connected to a bitline BL for sensing and a wordline WL for sensing, respectively. A wordline for writing intersects a bitline for writing above the spin filter transistors in such the at-state of being these lines are electrically insulated from other wires. As the rewrite word line and the rewrite bit line, the read bit line BL and the read word line WL may be used. FIG. 4(A) is a diagram showing a cell structure of this case. In FIG The wordline for writing and the bitline for writing may be combined with the aforementioned bitline BL for sensing and wordline WL for sensing, as shown in Fig. 4 (A). In the case of Fig. 4 (A), the a memory cell can be constituted~~formed by the a single spin-filter transistor alone and can have a very simplified structure for wiring. A filter transistor, and also a simple wiring arrangement can be adopted. Thus, the present memory cell arrangement makes it possible to easily configure a layout suitable for high-density integration ~~can be easily constituted~~. The same cell structure is used in FIG. 4(B). The example shown in Fig. 4 (B) also adopts a similar cell arrangement.

With reference to Fig. 4(B), a memory circuit according to the present embodiment will be described with reference to FIG. 4(B). In a memory circuit 41 according to this of the present embodiment, the second nonmagnetic electrode 4 as 4, which is the base of the spin filter transistor 1 (FIG. 1), is connected to a word line 42; the word line 42; a third nonmagnetic electrode 7 as 7, which is the collector electrode of the spin filter transistor 1, is connected to a bit line 43; the bit line 43 is connected via a load (R_L) 44 to a power source supply (V_{CC}) 45; 45 via a load (R_L) 44; and the first nonmagnetic electrode 3 as 3, which is the emitter electrode of the spin filter transistor 1 is grounded. A1, is connected to ground. Although a pure resistance is used as the load, in the illustrated example, an active load by the consisting of a transistor may be used.

To read stored When sensing information of stored in a specified memory cell, the specified word line a specific wordline 42 is selected to apply and a bias between is applied across the emitter and the base, the source-base junction, and a power supply voltage V_{CC} from the power source supply 45 is applied to the bit line 43 via the load resistance 44 to the bit line 43, 44. Then, the stored information is read according to sensed using the magnitude of an output voltage V_O appearing on that appears at the bit line 43. In FIG. 4(C), the The vertical axis indicates of Fig. 4 (C) shows collector current I_C . The horizontal axis indicates shows collector-emitter voltage V_{CE} , and an I_C - V_{CE} characteristic. The graph thus shows the I_C - V_{CE} characteristics of the spin filter transistor and a load straight line 46 by of the load resistance 44 are shown in the same drawing chart.

The output voltage V_O is determined from by the crossing point intersection of these characteristics. Output voltages in which Specifically, the output signals in the mutual cases where the magnetization states of configuration between the first and second ferromagnetic barrier layers 2 and 6 are is parallel and anti-parallel are $V_{O\uparrow\uparrow}$ and $V_{O\uparrow\downarrow}$, as shown in FIG. 4 (C). The absolute values of the $V_{O\uparrow\uparrow}$ and $V_{O\uparrow\downarrow}$ and the ratio of the $V_{O\uparrow\uparrow}$ and $V_{O\uparrow\downarrow}$ can be optimized by the means of circuit parameters (R_L and V_{CC}). Thus, using the nonvolatile memory device according to this of the present embodiment can obtain, output signals having a necessary magnitude and the of required magnitudes and a required ratio of output signals can be obtained without adjusting the structure of the device itself unlike the elements themselves, as in a MTJ.

The spin filter effect used in utilized by the transistor according to this embodiment is an effect using the spin split of the bands of the ferromagnetic substances and has a spin selectivity higher of the present embodiment is provided by the spin band splitting of the ferromagnet, such that a higher spin selectivity can be obtained than that of is possible with the TMR effect of the MTJ. When the base width is set below to be no more than the mean free path of the spin-polarized hot carriers and, the current transfer ratio α (defined as being equal to I_C/I_E) can be 0.5 or more when the relative magnetization state configuration between the first and second ferromagnetic barrier layers is parallel magnetization, the current transmission factor α (defined by I_C/I_E) can be 0.5 or above. When it is anti-parallel. However, when the relative magnetization configuration is antiparallel, the current transmission factor is very transfer ratio is extremely small. The

~~Thus, the change in the current transmission factor in the case of transfer ratio between parallel magnetization and anti-parallel magnetization is further even more amplified, seen from the in terms of current amplification factor β gain β (defined by $\beta = I_E / I_B$). The above peripheral circuits optimize I_B . By optimizing the output signal using the above-described peripheral circuitry with reference to the output characteristics of the spin-filter transistor which is largely different in that vary greatly depending on the magnetization state. The configuration, output signals of desired absolute values of output signals and their desired ratio of output signals can be easily obtained.~~

~~A Hereafter a nonvolatile memory circuit using the transistor having an output characteristic depending utilizing a transistor (to be hereafter referred to as a "spin transistor") with output characteristics that depend on the spin direction of the spin of carriers (hereinafter, called a "spin transistor") will be described.~~

~~The memory circuit according to of the present invention relates to a nonvolatile memory circuit using the utilizing a spin transistor. The A spin transistor includes ferromagnetic substances a ferromagnet such as a ferromagnetic metal and/or a ferromagnetic semiconductor and controls the. The output characteristics are changed by controlling the spin direction of the spin of carriers according to depending on the magnetization state to change the output characteristic configuration of the ferromagnet. Information is stored based on the magnetization state of the ferromagnetic substances in the spin transistor. The output characteristic of the transistor reflecting the magnetization state in the spin transistor is used to read the information. A one in terms of the magnetization configuration of the ferromagnet inside the spin transistor, and the stored information is sensed using the output characteristics of the transistor that reflect the magnetization configuration inside the spin transistor. Using the spin transistor, a 1-bit nonvolatile memory cell can be constituted by one configured with a single spin transistor. The values Furthermore, the value of the output signal signal corresponding to the stored information can be optimized by the peripheral circuitry connected to the memory cell.~~

~~In greater detail Specifically, the spin transistor has comprises at least one ferromagnetic each of a ferromagnet layer (free layer) capable of independently controlling the direction of relative magnetization by configuration using a magnetic field and at least one ferromagnetic or the like, and a ferromagnet layer (pin layer) in which the direction of magnetization is fixed with a fixed relative magnetization configuration or having a larger coercivity larger than that of the free layer and is a transistor capable of controlling the output characteristic. The output characteristics of the transistor according to can be controlled by the relative directions of magnetization configuration of the free layer and the pin layer even under the same bias. The direction of condition. By changing the relative magnetization configuration of the free layer is changed by using a magnetic field. The relative magnetization states, for example, the relative magnetization configuration of the free layer and the pin layer can be two states of parallel magnetization and anti-parallel magnetization. The two magnetization states correspond to rendered into two configurations, namely, parallel or antiparallel. These two magnetization configurations are associated with binary stored information.~~

~~The In the spin transistor can obtain the output characteristic according to the~~

magnetization state in the transistor, based on a conductive phenomenon ~~changed that~~ varies depending on the spin direction of the spin of carriers, such as spin-dependent scattering, tunneling magnetoresistance effect, and/or spin filter effect, output characteristics corresponding to the internal magnetization configuration of the transistor can be obtained. The spin transistor ~~has comprises~~ comprises a first electrode structure for injecting spin-polarized carriers, a second electrode structure for receiving the spin-polarized carriers, and a third electrode structure for controlling the amount ~~quantity~~ of the spin-polarized carriers conducted that are transported from the first electrode structure to the second electrode structure.

The spin transistor ~~is operated based~~ transistors operate on the same operating principle as a typical transistor ~~other than the conductive phenomenon depending on the spin.~~ The spin transistor ~~can be classified as a principle as that of the conventional transistors with the exception of the involvement of the spin-dependent conduction phenomenon.~~ Thus, the spin transistors can be classified into current-driven type transistor ~~transistors~~ such as a bipolar transistor ~~or a transistors~~, and voltage-driven type transistor ~~transistors~~ such as an electric field effect transistor. ~~transistors.~~ In terms of the current-driven type transistor, the first electrode structure corresponds to ~~the~~ emitter, the second electrode structure corresponds to ~~the~~ collector, and the third electrode structure corresponds to ~~the~~ base. ~~The spin-~~ The spin-filter transistor described in ~~this~~ with reference to the present embodiment is classified as the a current-driven type transistor. In terms of the voltage-driven type ~~driven~~ transistor, the first electrode structure corresponds to the source, the second electrode structure corresponds to the drain, and the third electrode structure corresponds to the gate. The output current in the spin transistor (collector current or drain current) ~~in the spin transistor is changed according to the magnetization state of the ferromagnetic substances included in the spin transistor~~ changes depending on the magnetization configuration of the ferromagnet contained in the spin transistor even under the same bias condition.

The details of the spin transistor will be described later. ~~Typical~~ In the following, the general output characteristics of a spin transistors and a nonvolatile memory using the spin transistors will be described. A magnetic field is ~~applied~~ employing a spin transistor will be described. It is assumed in the following that the relative magnetization configuration between the free layer and the pin layer can be rendered parallel or antiparallel by applying a magnetic field to the free layer in the spin transistor to make it possible to realize parallel magnetization or anti-parallel magnetization of the relative magnetization state of the free layer and the pin layer. The magnetization state can stably exist. It is also assumed that the magnetization configuration can exist stably unless a magnetic field above exceeding the coercivity of the free layer is applied.

~~FIG. 5 (A) schematically shows an example of an output characteristic of the current driven type spin transistor. Like a typical current driven type~~ the output characteristics of a current-driven spin transistor. As in a conventional current-driven transistor, although the collector current I_C can be controlled according to by the magnitude of the base current I_B . ~~The magnitude of the collector current depends on the magnetization state of the ferromagnetic substance included in the spin transistor. In FIG. 5(A), when applying, it is also dependent on the magnetization configuration of the ferromagnet~~

contained in the spin transistor. In the example of Fig. 5 (A), even when the bias applied to the spin transistor is the same bias to the spin transistor ($I_B = I_{B1}$), the collector current $I_{C1\uparrow}$ is large in the case of parallel magnetization and is large, whereas the collector current $I_{C1\downarrow}$ in the case of antiparallel magnetization is small in anti-parallel magnetization.

FIG. 5 (B) schematically shows an example of the output characteristics of the voltage-driven type spin transistor. Like a As in a conventional field-effect transistor, such as a typical MOS transistor, when the gate-source voltage (V_{GS}) is smaller than the threshold value V_T ($V_{GS} < V_T$), the spin transistor is in the non-conductive off state and a drain current is hardly produced. When applying the V_{GS} above the V_T , the spin transistor is brought to the conductive state. Under the same bias ($V_{GS} = V_{GS1}$), when the ferromagnetic substance included in the spin transistor has where hardly any drain current flows. Although the spin transistor conducts when a V_{GS} exceeding V_T is applied, the drain current value differs depending on whether the ferromagnets contained in the spin transistor have parallel magnetization or anti-parallel magnetization, a drain current value is different. In FIG. 3(B), in antiparallel magnetization, even under the same bias condition ($V_{GS} = V_{GS1}$). In the case that it has parallel magnetization of Fig. 3 (B), the drain current $I_{D1\uparrow}$ is large, and in the case that it has anti-parallel magnetization, larger for parallel magnetization whereas the drain current $I_{D1\downarrow}$ is small for antiparallel magnetization.

Thus, the spin transistor, whether it is current-driven or voltage-driven, can electrically detect the magnitude of the relative directions of magnetization configuration of the free layer and the pin layer included in the devices of the current driven type and the voltage driven type based on contained in the device using the magnitude of the collector current or the drain current. As described mentioned above, the ferromagnetic substances can stably hold the direction of magnetization relative magnetization configuration in the ferromagnet can exist stably unless a magnetic field above exceeding the coercivity of the free layer from outside is externally applied. The Thus, the spin transistor can store, in nonvolatile manner, binary information by allowing in a nonvolatile manner by rendering the relative magnetization state configuration of the free layer and the pin layer included contained in the device to be parallel magnetization or anti-parallel magnetization. A one-parallel or antiparallel. Therefore, using the spin transistor, a 1-bit nonvolatile memory cell can be constituted only by one with a single spin transistor.

Taking the case of using the voltage driven type spin transistors as an example In the following, a nonvolatile memory using the spin transistors employing a voltage-driven spin transistor will be described below in detail. A nonvolatile memory using the current driven type spin transistors as memory cells can be constituted in the same manner. The same configuration can be adopted where a current-driven type spin transistor is used in a memory cell.

FIG. 6(A) is a diagram showing a structural Fig. 6 (A) shows an example of memory cells using spin transistors. FIG. 6(B) is a diagram showing a structural the memory cell using the spin transistor. Fig. 6 (B) shows an example of a memory circuit formed based on the memory cells. The relation of FIGS. 6(A) and 6 configured with the memory cell. The relationship between Fig. 6 (A) and Fig. 6 (B) is the same as that of FIGS between Fig. 4 (A) and Fig. 4 (B). In the memory cell circuit shown in FIG. 6 (A), a number of spin transistors 150 are arrayed in a matrix, and source with the sources S is grounded to

connect drain D and gate G to read bit line BL and read word line WL, respectively. A rewrite word line and a rewrite bit line and the drains D and the gates G connected to a bitline BL for sensing and a wordline WL for sensing, respectively. A wordline for writing and a bitline for writing are arranged to cross each other on intersect one another above the spin transistors 150 in the state of being a manner electrically insulated from other wires. As the rewrite word line and the rewrite bit line, the read bit line BL and the read word line WL may be used. FIGS. 6(A) and 6(B) are diagrams showing the structure of this case. In FIGS. 6(A) and 6(B), the memory cell can be constituted by one. The wordline for writing and the bitline for writing may be combined with the aforementioned bitline BL for sensing and the wordline WL for sensing, as shown in Fig. 6 (A) and (B). In the case of Fig. 6 (A) and (B), a memory cell can be configured with a single spin transistor and can have, and also a very simplified structure for simple wiring arrangement can be adopted.

In particular, Particularly in the case of a voltage-driven type spin transistor having a form, which has a similar form to that of a MOS transistor, the source is shared between adjacent memory cells. A layout suitable for microfabrication can be easily constituted obtained by, for example, causing adjacent memory cells to use the source in common.

———— The rewrite/read bit line and rewrite/read word line are simply called bit line BL and word line. The aforementioned writing/sensing bitlines and writing/sensing wordlines will be hereafter referred to simply as a bitline BL and a wordline WL, respectively.

———— Information is rewritten by flowing electric currents to the bit line BL and the word line WL crossing on the. Information can be written over by causing a current to flow through the bitline BL and the wordline WL that intersect over a selected memory cell to invert and then inverting the free layer of the selected memory cell by with a synthesized composed magnetic field induced by the electric currents flowing to current through the respective wires. In this case, in order that then not to allow non-selected cells connected to the same bit line bitline BL or word line wordline WL as those of the selected cell is not to be inverted by magnetization inverted, current values flowing to the respective wires are set so, a current value that is caused to flow in each line is set in advance such that no magnetization inversion does not occur in the is caused by a magnetic field from emitted by one of the wires.

In reading When sensing information, a voltage is applied to the word line wordline WL connected to the of a selected cell so as to cause the spin transistor to conduct the spin transistor, and then a voltage is applied to the bit line bitline BL to detect the magnitude of the drain current. Based on the magnitude of the drain current, the relative magnetization state configuration of the free layer and the pin layer can be detected. —FIG

Fig. 6 (B) is a memory circuit connected to output terminal V_O and source voltage V_{DD} branched shows the memory circuit shown in Fig. 6 (A), to a bitline end of which an output terminal V_O is connected, with a branch from the output terminal V_O via a load to the bit line end of the memory circuit shown in FIG. 6(A). FIG. 6(C) shows a static characteristic connected to a power supply voltage V_{DD} via a load. Fig. 6 (C) shows the static characteristics and operating points of the memory cell shown in FIG. 6 (B). Here, Although an active load 160 by a depression consisting of a depletion-type MOS transistor

is used as the load. A in this example, pure resistance may be used, as shown in FIG. 4(B). As shown in FIG. 6(C), Fig. 4 (B). Referring to Fig. 6 (C), when sensing information, a gate voltage V_{GS} is applied to the gate of the spin transistor 150 at reading information to apply the source voltage V_{DD} via the load to the bit line BL. The operating points by the active load are moved on the load curve in FIG. 6(C) according to the magnetization state of and a power supply voltage V_{DD} is applied to the bitline BL via a load. This causes the operating point due to the active load to move along the load curve shown in Fig. 6 (C) (between P11 and P12) depending on the magnetization configuration between the pin layer and the free layer (P11 and P12 in the drawing). The output signals V_O in parallel magnetization and anti parallel magnetization are $V_{O\uparrow\uparrow}$ and $V_{O\downarrow\uparrow}$ in the drawing. As a result, the output signal V_O would be $V_{O\uparrow\uparrow}$ or $V_{O\downarrow\uparrow}$ for the parallel or antiparallel magnetization, respectively. The absolute values and of the ratio of ($V_{O\uparrow\uparrow}/V_{O\downarrow\uparrow}$) of the respective output signals and their ratio ($V_{O\uparrow\uparrow}/V_{O\downarrow\uparrow}$) can be optimized by using the transistor characteristics of the active load and/or the parameters of the peripheral circuit/circuitry, such as V_{DD} . For instance, the cross point For example, by optimizing the intersection of the static characteristics of the spin transistor and the load curve by of the active load is optimized. When drain current ratio $I_{O\uparrow\uparrow}/I_{O\downarrow\uparrow}$ is small, a large output signal ratio can be obtained. When the values of $I_{O\uparrow\uparrow}$ and $I_{O\downarrow\uparrow}$ are varied by the memory cell and even when the drain current ratio $I_{O\uparrow\uparrow}/I_{O\downarrow\uparrow}$ is small. Further, even if there are variations in the values of $I_{O\uparrow\uparrow}$ and $I_{O\downarrow\uparrow}$ among memory cells, the fluctuation in the output voltage can be almost eliminated as long as the saturation current of the active load is larger than $I_{O\downarrow\uparrow}$ and is $\uparrow\uparrow$ and smaller than $I_{C\uparrow\uparrow}$, the output voltage can be hardly changed. Since $\uparrow\uparrow$. Because no sense amp is amplifiers are used for readingsensing information, a high-speed reading is possible. The speed sensing can be performed. Thus, the memory circuit of this the present embodiment has the advantages that an output signal having is advantageous in that output signals of a desired magnitude can be easily obtained and in that a high-speed read is possible.sensing can be performed.

In the conventional memory cell usingutilizing the prior art MTJ and MOS transistor, antransistors, output voltages according to produced by the resistance of the MTJ is readare sensed by a sense amp. Theamplifier. In this case, however, because the output voltage is determined by a the value of the current value flowing tothrough the MTJ and anthe impedance of the MTJ (junction resistance) of, the MTJ. The output voltage ratio cannot be freely adjusted by the peripheral circuitry.

~~The~~In the following, the structure of a spin transistor applicable tothat can be used in the nonvolatile memory circuit according to thisof the present embodiment will be described with reference to the drawings. FM is an abbreviation of a, using abbreviations FM for ferromagnetic metal, FS is an abbreviation of anfor electrically conductive ferromagnetic semiconductor, IFS is an abbreviation of anfor insulating ferromagnetic semiconductor, and NM is an abbreviation offor a nonmagnetic substance. An material. In particular, an “NM metal denotes” designates a nonmagnetic metal, and an “NM semiconductor denotes” designates a nonmagnetic semiconductor. The First, a group of spin transistors of the current-driven type spin transistors will be described.

~~FIG~~Fig. 7 isshows an energy band diagram of a hot -electron transistor type spin

transistor. A spin transistor 200 ~~has~~comprises an emitter 201 and a base 205 ~~made of that~~are formed by FM or FS. ~~In greater detail~~ Specifically, the spin transistor 200 ~~has~~comprises emitter 201 ~~made of~~formed by FM (or FS); ~~an~~ emitter barrier 203 ~~made of~~formed by NM; ~~the~~ base 205 ~~made of~~formed by FM (or FS); collector barrier 207 ~~made of~~formed by NM; and a collector 211 ~~made of~~formed by NM. ~~As the~~ NM, may be either a nonmagnetic metal or a nonmagnetic semiconductor can be used.

In the spin transistor 200 shown in ~~FIG~~Fig. 7, spin-polarized hot carriers are tunnel-injected from the emitter 201 to the base 205 via the emitter barrier 203 ~~to the base 205~~. 203. When the emitter 201 and the base 205 ~~have~~possess parallel magnetization, the injected spin-polarized hot carriers ~~are hardly subject to~~experience spin-dependent scattering ~~in within~~ the base 205. ~~When a~~ Thus, by setting the base width ~~is set so~~such that the spin-polarized hot carriers can be ballistically transmitted ~~pass~~ through the base 205, ~~they cross over~~205 ballistically, the carriers can be transported beyond the collector barrier 207 to the collector 211. ~~The same~~ This is a transistor operation ~~as~~similar to that of a typical ~~conventional~~ hot electron transistor ~~is performed~~.

~~When~~On the other hand, when the emitter 201 and the base 205 ~~have anti-parallel~~possess antiparallel magnetization, the spin-polarized hot carriers injected from the emitter 201 ~~into~~to the base 205 lose energy ~~by due to~~ the spin-dependent scattering ~~in within~~ the base 205 ~~to be a base current without crossing over~~ and are therefore unable to overcome the collector barrier 207. ~~When~~207, resulting in a base current. Namely, when the emitter 201 and the base 205 ~~have anti-parallel~~ magnetization, the current transmission factor is lower than the case that both have parallel magnetization. When applying the same bias ~~possess antiparallel~~ magnetization, the current transfer ratio drops as compared with the case of parallel magnetization. Therefore, even if the same bias is applied to the spin transistor 200, the current transfer ratio or current gain ~~varies depending on~~ the difference in the relative magnetization state ~~of configuration between~~ the emitter 201 and the base 205 ~~makes the current transmission factor or the current amplification factor different~~. 205. The spin transistor 200 can be operated at room temperature by suitably ~~appropriately~~ selecting the collector barrier height ~~of the collector barrier~~. The spin transistor 200 ~~must have a large base width, for example~~.

In the spin transistor 200, if the ratio of the current transfer ratio in the case where the emitter-base junction has parallel magnetization and that in the case where the junction has antiparallel magnetization is to be increased, the base width must be sufficiently large so that the spin-dependent scattering can effectively function ~~to increase the ratio of the current transmission factors in the case that the emitter and the base have parallel magnetization and the case that they have anti-parallel magnetization~~. When the base width is increased and the emitter and the base have parallel magnetization, the current transmission factor is smaller and is below 0.5 so that a trade-off in which the. However, when the base width is increased, the current transfer ratio becomes smaller even when the emitter-base junction has parallel magnetization, dropping below 0.5, for example. Thus, there is a tradeoff between an increase in the base width and a decrease in amplification function ~~is lost~~ exists.

~~FIG~~Fig. 8 ~~is~~shows an energy band diagram of a hot-electron transistor type spin transistor using thermal release as a spin injection ~~in which thermionic emission is utilized~~

as a mechanism to ~~a~~for injecting spin polarized carriers to the base. As shown in ~~FIG~~Fig. 8, a spin transistor 220 ~~has~~comprises an emitter 221 ~~made~~formed by FM (or FS); a base 225 ~~made~~formed by FM (or FS); and an emitter barrier 223 ~~made~~of NM provided between both. It further has a collector barrier 227 ~~of~~ NM, and a collector 231 ~~of~~ NM disposed between the emitter and the base and formed by NM. Furthermore, on the opposite side ~~of~~to the junction ~~of~~between the base 225 and the emitter barrier 223. A nonmagnetic semiconductor can be used for the 223, there is provided a collector barrier 227 formed by NM and a collector 231 formed by NM. The emitter barrier 223 and the collector barrier 227. A 227 may be formed by a nonmagnetic semiconductor. The collector 231 may be formed by a nonmagnetic semiconductor or a nonmagnetic metal ~~can be used for the collector 231.~~

~~An~~Between the emitter 221 and the emitter barrier 223, an ohmic contact or a tunnel contact is formed ~~between~~. Between the emitter 221 ~~base 225 and the emitter barrier 223.~~ A junction is formed between the base 225 and the emitter barrier 223 ~~or 223,~~ and between the base 225 and the collector barrier 227 ~~so as to have 227,~~ a junction exhibiting a band discontinuity as shown in FIG. 9. The Fig. 9 is formed. This band discontinuity can be realized by a Schottky junction between the NM semiconductor and FM ~~and,~~ or by a heterojunction between the NM semiconductor and FS. Alternatively, a Schottky junction ~~is~~may be formed ~~of~~between FS and FM, ~~and the resultant Schottky barrier produced in this case is an~~may be used as the emitter barrier, ~~with FS is an emitter,~~ and FM is ~~a~~functioning as emitter and base, respectively.

The spin-polarized carriers diffused from the emitter 221 to the emitter barrier 223 ~~by applying through the application of~~ a bias to the base 225 with respect to the emitter 221 are injected ~~to the base 225 as hot carriers into the base 225 by thermal release by thermionic emission.~~ When the emitter 221 and the base 225 have ~~possess~~ parallel magnetization, the spin-polarized hot carriers injected into the base 225 can reach the collector without being subject to spin-dependent scattering. ~~When~~subjected to spin-dependent scattering. However, ~~when~~ the emitter 221 and the base 225 have ~~anti-parallel~~possess antiparallel magnetization, the spin-polarized hot carriers ~~become~~are rendered into a base current by spin-dependent scattering. ~~The spin.~~ In this transistor 220 ~~use~~too, because it utilizes spin-dependent scattering in the base. ~~Like the,~~ there is a tradeoff, as in the above-described spin transistor 200, ~~a trade-off relation exists between the ratio of the current transmission factor transfer ratio in the case of parallel magnetization and anti-parallel that in the case of antiparallel magnetization, and the current transmission factor in transfer ratio in the case of parallel magnetization.~~ As The transistor 220, however, is advantageous as compared with the spin transistor 200 ~~using 200,~~ which utilizes tunnel injection, ~~there are characteristics in that a larger current driving force can be large obtained and in that a room-temperature operation can be easily realized.~~

~~FIG~~Fig. 9 ~~is~~shows an energy band diagram of a hot-electron transistor type spin transistor ~~using~~utilizing the spin-filter effect. Although the transistor ~~is~~has already been described in detail, its characteristics will be briefly described. A spin transistor 240 shown in ~~FIG~~Fig. 9 ~~has~~comprises an emitter barrier 243 and a collector barrier 247 ~~made of that are formed by IFS.~~ From Via an emitter 241 ~~made of 241,~~ which is formed by an NM semiconductor (or an NM metal), ~~only the carriers having one of spins by the spin filter~~

effect of the emitter barrier 243 with one spin can be selectively injected into the base 245 made of 245, which is formed by an NM semiconductor (or an NM metal). The, through the spin-filter effect provided by the emitter barrier 243. When the base width is set below to be not greater than the mean free path of the spin-polarized hot carriers, the spin-polarized hot carriers injected into the base 245 are transported to the base 245 ballistically conducted through the base 245. At. In this time case, the spin transistor 240 is biased so such that the spin-polarized hot carriers are injected into the energy split width of the between an up spin band of the collector barrier 247 (the a spin band edge indicated designated by the upward arrow in FIG Fig. 9) and the a down spin band (the a spin band edge indicated designated by the downward arrow in FIG Fig. 9). When the emitter barrier 243 and the collector barrier 247 have parallel magnetization, the spin-polarized hot carriers injected into the base 245 can overcome the barrier by of the spin band having a low of lower energy in the collector barrier 247 by through the spin filter effect of the collector barrier 247 247, and can be propagated therefore propagate to a collector 251 of 251, which is formed by an NM semiconductor (or an NM metal). When. On the other hand, when the emitter barrier 243 and the collector barrier 247 have anti-parallel antiparallel magnetization, most of the spin-polarized hot carriers become a base current without crossing over cannot overcome the collector barrier 247 by the spin filter effect of the collector barrier 247 because of the spin-filter effect of the collector barrier 247, resulting in a base current.

In Thus, in the spin transistor 240, the current transmission factor transfer ratio (or the current amplification factor) is different according to gain) differs depending on the relative directions of magnetization configuration of the emitter barrier 243 and the collector barrier 247. The. Because the spin filter effect has provides a very large high spin selectivity. The ratio of the current transmission factors in, the ratio of current transfer ratio in the case of parallel magnetization and anti-parallel that in the case of antiparallel magnetization can be increased in the transistor.

The spin transistor 240 can sufficiently decrease the base width. Unlike Furthermore, in the spin transistor using spin 240, the base width can be made sufficiently small. Therefore, in contrast to the spin transistor that utilizes spin-dependent scattering, as in the cases shown in FIGS. 7 and 8, there is the advantage that a trade-off related to the base width Figs. 7 and 8, the spin transistor 240 is advantageous in that there is no tradeoff between the current amplification factor gain relating to the base width and the spin selectivity does not exist.

FIG Fig. 10 is shows an energy band diagram of a tunnel base transistor type spin transistor. As shown in FIG Fig. 10, in a tunnel base transistor type spin transistor 260, a p-type (or n-type) FS is used for 260 comprises an emitter 261 and a collector 265 and an n-type (or p-type) NM semiconductor is used for a tunnel base 263. It is preferable to use that are formed by a p-type (or an n-type) FS, and a tunnel base 263, which is formed by an n-type (or a p-type) NM semiconductor. In the emitter-base junction and in the base-collector junction, a heterojunction of type II is preferably used so that the base 263 is becomes a barrier to the holes (or electrons) between the emitter and the base and between the base and the collector. The base width is smaller so as to produce a tunnel reduced sufficiently that a tunneling current from the emitter to the collector is produced.

In the structure shown in FIG. 10, when the emitter 261 and the collector 265 have parallel magnetization, the carriers having a number of spins of with the majority spin in the emitter can be easily tunneled transported to the collector 265 and through tunneling, namely, the tunnel conductance is large. However, when the emitter 261 and the collector 265 have anti-parallel magnetization, the tunnel conductance is small reduced by the tunneling magnetoresistance (TMR) effect (TMR effect). Thus, the magnitude of the collector current can be controlled according to the relative magnetization state of configuration between the emitter 261 and the collector 265.

If the TMR ratio in the spin transistor 260 can be large increased, the change in the collector current depending that depends on the magnetization state of the configuration between emitter and the collector can be increased. To effectively exhibit In order to allow the TMR effect to be effectively exhibited in the spin transistor 260, preferably, a depression layer is not expanded to it is preferable to prevent the depletion layer from expanding towards the collector side when applying a reverse bias to is applied across the base-collector junction. When the depression It is noted, however, that if the depletion layer is expanded to towards the base side, the possibility that, a problem arises in the saturation characteristic of could possibly arise in the collector current exist saturation characteristics.

When the base layer is doped with high density so as not to expand the depression layer to the base layer in the spin transistor 260 and the depression layer of is heavily doped so as to prevent the spreading of the depletion layer and to cause the depletion layer in the base-collector junction is expanded to spread towards the collector side, the TMR effect in the base cannot be expected and. However, the carriers injected into the collector produce resistance by are subjected to spin-dependent scattering in the collector. Using the spin resistance, resulting in increased resistance. By utilizing this spin-dependent scattering can change, the magnitude of the collector current according to can be varied by the magnetization state of the emitter and the collector. The change in resistance by the spin configuration in the emitter-collector junction. It is possible, however, that the effect is not so large as that obtained with the TMR effect because the resistance change through spin-dependent scattering is small. As compared with using the TMR effect, the effect may be not high.

Hereafter, a group of voltage-driven type spin transistors will be described with reference to the drawings.

FIG. 11 is a diagram showing the shows a cross-sectional structure section of a MOS transistor type spin transistor. As shown in FIG. 11, the MOS transistor type spin transistor 300 has a structure in comprises an NM semiconductor 301 on which a source 303 made of formed by FM, a drain 305 made of formed by FM, and a gate electrode 311 are formed, the gate electrode via a gate insulator film 307 are formed on an NM semiconductor 301, insulating film 307. A Schottky junction of the FM and an NM semiconductor is used for the source 303 and the drain 305. Other structure is The other structures are the same as that of a typical those of a conventional MOS transistor.

Spin-polarized carriers injected from the source 303 into a channel formed directly below the gate insulating film 307 in of the NM semiconductor 301 pass

through the channel to the drain 305 (~~hereinafter, for simplification hereafter,~~ the influence of the Rashba effect ~~by due to~~ the gate electric field of the spins injected into the channel is neglected). ~~will be ignored for simplicity).~~ When the source 303 and the drain 305 have parallel magnetization, the spin-polarized carriers injected into the drain 305 are not subject to spin-dependent scattering. When they have ~~anti-parallel~~ antiparallel magnetization, however, resistance by spin-dependent scattering is produced in the drain electrode 305.

~~In~~ Thus, in the transistor 300, the mutual conductance is ~~different according to~~ differs depending on the relative directions of magnetization ~~of configuration between~~ the source and the drain.

~~FS can be also used for the~~ The source 303 and the drain 305 ~~to form~~ may be formed by FS, and a pn junction is formed between it each and the semiconductor 301 ~~to form a source and a drain.~~ 301.

~~FIG~~ Fig. 12 is a diagram showing the shows a cross-sectional structure section of a modulation-doped transistor type spin transistor. ~~A~~ The spin transistor 320 ~~has~~ comprises a source 323 ~~made of FM (or FS) to in contact with the two-dimensional carriers gas produced at the interface of boundary between a first NM semiconductor 321 and a second NM semiconductor 327, 327;~~ a drain 325 ~~made of~~ formed by FM (or FS); and a gate electrode 331. ~~It is the same as a typical modulation-doped transistor except~~ The spin transistor 320 is identical to a conventional modulation-doped transistor with the exception that the source 323 and the drain 325 are made of ferromagnetic substances formed by a ferromagnet.

Spin-polarized carriers are injected from the source 323 ~~into~~ to a channel 333 formed by the two-dimensional carrier gas. The spin-polarized carriers ~~which have reached that reach~~ the drain 325 have different mutual conductance ~~according to~~ depending on the relative directions of magnetization configuration of the source 323 and the drain 325 due to spin-dependent scattering in the drain 325.

~~FIG~~ Fig. 13 is shows a cross-sectional view section of a MOS transistor type spin transistor using FS ~~for in which the channel region A is formed by FS.~~ The spin transistor 340 shown in ~~FIG~~ Fig. 13 has a structure in comprises FS 341 on which a source 343 ~~made of~~ formed by FM, a drain 345 ~~made of~~ formed by NM (or FM or FS), and a gate electrode 351 via a gate insulating film 347 are formed ~~on an FS 341.~~ A Schottky junction of the FM and FS is used for the source 343. Other structure is the same as that of a typical in the source 343; except for that, the structure is identical to that of a conventional MOS transistor.

Spin-polarized carriers are tunnel-injected from the source 343 ~~via~~ into the channel 341 by tunneling through the Schottky barrier ~~into the channel 341.~~ The. Based on the TMR effect and the spin-dependent scattering in the channel of FS 341 during tunneling injection, a mutual conductance depending that depends on the relative directions of magnetization configuration of the source 343 and the FS 341 is realized by the TMR effect at the tunnel injection and spin-dependent scattering in the channel of the FS 341.

~~A~~ Fig. 14 shows a cross section of a spin transistor 360 ~~showing its cross-sectional structure in FIG. 14 is a spin transistor having comprising a tunnel junction structure interposing in which an insulating NM tunnel barrier 365 is disposed between a source 361~~

~~made or formed by FM (or FS) and a drain 363 made or formed by FM (or FS) and arranging a. It is a spin transistor with the gate electrode 371 so as to apply disposed such that an electric field can be applied to the tunnel barrier 365.~~

~~The film thickness of the tunnel barrier 365 is preferably set to a thickness so such that no Fowler-Nordheim (FN) tunneling occurs when applying only a bias between the source and the drain. The bias is applied. A triangular potential at the band edge of the tunnel barrier band edge produced by applying a bias between across the source and the drain junction is changed varied by at the gate voltage in order to induce the FN tunneling to and obtain a drain current.~~

~~Spin-polarized carriers injected from the source 361 are subject to spin-dependent scattering in the drain 363 according to depending on the relative magnetization state configuration of the source 361 and the drain 363. The Thus, the mutual conductance of the transistor can be controlled by the relative directions of magnetization of configuration between the source and the drain.~~

~~A Fig. 15 shows a cross section of a spin transistor 380 showing its cross sectional structure in FIG. 15 replaces the tunnel barrier of 380, which is similar to the spin transistor 360 shown in FIG. 14 with the exception that the tunnel barrier comprises a tunnel barrier 385 made or formed by IFS. A While a source 381 must be of FM or FS. A, a drain 383 need may not be a ferromagnetic substance. The barrier height of ferromagnet. In the IFS tunnel barrier layer 385 is different according to the 385, the barrier height differs depending on the spin direction of the spin of carriers. When the source 381 and the tunnel barrier 385 have parallel magnetization, a bias is carriers. A bias is therefore applied between the source and the drain and between across the source and the gate so junction such that the transistor is brought to the conductive state. conducts when the source 381 and the tunnel barrier 385 have parallel magnetization. Under the same bias condition, when the source 381 and the tunnel barrier 385 have anti-parallel antiparallel magnetization, the tunnel barrier height of the tunnel barrier as seen from a number of spins of the majority spin in the source 381 is increased. The tunnel increases. As a result, the tunneling probability of the spin-polarized carriers is decreased to reduce the decreases, leading to a decrease in drain current. The spin selectivity by the spin filter effect is very large. When using a ferromagnetic substance having a large spin polarizability as the source 381, the mutual conductance according to Because the spin selectivity provided by this spin-filter effect is extremely large, the change in mutual conductance depending on the relative directions of magnetization configuration of the source and the drain can be largely changed. increased by using a ferromagnet with a large spin polarization in the source 381.~~

~~The Any of the above-described various spin transistors can may be used as the memory cells for the memory circuit shown in FIG. 4 or FIG. 6.~~

~~It is also possible to form a structure configuration in which the sources of the two voltage-driven type spin transistors shown in FIGS. 11, 14, and 15 are shared as one source. FIG. 16(A) is a diagram showing a structural example of memory cells having a shared source structure. FIG. 16(B) is a diagram showing a cross sectional structural example have a common source. Fig. 16 (A) shows an example of a memory cell of a common-source configuration. Fig. 16 (B) shows a cross section of the memory cells having a shared of a common-source structure. configuration.~~

The memory cell structure shown in FIGS. 16 (A) and 16(B) comprises a first spin transistor Tr1 and a second spin transistor Tr2 that are disposed adjacent each other, word line WL shared to one another; a wordline WL connecting a gate electrode G1 of the first spin transistor Tr1 and a gate electrode G2 of the second spin transistor Tr2; a first bit line BL1 connected to a first drain D1 of the first spin transistor Tr1; a second bit line BL2 connected to a second drain D2 of the second spin transistor; a ferromagnetic source S shared between common to the first and second spin transistors Tr1 and Tr2, and a wire grounding it. Using the above structure shares the source provides a2; and a line connecting the common source to ground. In this configuration, the common source makes the cell structure suitable for higher density integration.

To minimize a leak current at non conduction, in particular, the voltage-driven type spin transistors shown in FIGS. 11, 14 and 15, it is preferable to use Figs. 11, 14, and 15 preferably comprise a highly insulating substrate, such as an SOI substrate having a high insulation, as shown in FIG. 16(B). Fig. 16 (B), so as to reduce leakage current when the transistor is off.

As described above, the spin filter transistor according to the embodiments of the present invention and various spin transistors shown in this embodiment have a characteristic capable of controlling an output characteristic according to the relative directions of magnetization of the pin layer and the according to the various embodiments of the present embodiment are characterized in that the output characteristics can be controlled by the relative magnetization configuration of the pin layer and free layer included in within the device. The relative magnetization state has a nonvolatile characteristic capable of holding the state without supplying an electric power. The relative magnetization states can be stored as configuration is nonvolatile, namely, the device does not require the feeding of power for retaining the magnetization configuration. Thus, the device can store binary information in nonvolatile manner. Using the above output characteristic can electrically detect terms of the relative magnetization state. A one configuration in a nonvolatile fashion. Further, using the aforementioned output characteristics, the relative magnetization configuration can be electrically detected. Thus, a 1-bit nonvolatile memory cell can be configured only by one with a single spin transistor. Using the nonvolatile memory circuit using the comprising a spin transistor according to this embodiment can freely design the magnitude of output signals and the embodiments of the invention, the ratio of output signals as well as their magnitudes with respect to the stored information can be freely designed.

Thus, using the spin transistor according to these embodiments of the present invention and a memory circuit using the same can increase comprising the spin transistor, the operating speed and the level of integration of the nonvolatile memory circuit can be increased.

While the present invention has been described above along with reference to various embodiments. The thereof, the present invention is not limited to these. It is apparent by any of these embodiments. It should be obvious to those skilled in the art that various modifications, improvements and combinations can be made.

INDUSTRIAL APPLICABILITY

~~As described above,~~In accordance with the spin -filter transistor of the present invention ~~can largely change an output characteristic according to,~~ the output characteristics can be greatly changed by the relative directions of magnetization of configuration of the ferromagnetic barrier layers.

~~The~~A nonvolatile memory circuit ~~using, as comprising a memory cells, the cell employing this spin -filter transistor and another~~or a spin transistor having a characteristic equal to that of this ~~with equivalent characteristics can store binary information according to in terms of the relative directions of magnetization of ferromagnetic substances included configuration of ferromagnets contained in the transistor and can electrically detect the.~~ The relative directions of magnetization. Using configuration can also be detected electrically. Furthermore, using the nonvolatile memory circuit of the present invention can freely design, the output signals with respect to the stored information. A high- can be freely designed. Using such a spin transistor, a high-speed and high integration-density nonvolatile memory circuit with high density integration constituting a one- can be realized that comprises a 1-bit nonvolatile memory cell only by one made up of a single transistor can be realized.

CLAIMS

1. A transistor comprising :
 - a spin injector for injecting spin-polarized hot carriers by a spin -filter effect; and
 - a spin analyzer for selecting the thus injected spin-polarized hot carriers by the spin -filter effect.
2. The transistor according to claim 1, wherein said spin injector has comprises:
 - ~~a first ferromagnetic barrier layer capable of tunneling carriers by applying a voltage at both ends, through which the carriers can be transported by tunneling upon application of a voltage across said first ferromagnetic barrier layer;~~
 - a first nonmagnetic electrode layer joined to one end surface of said first ferromagnetic barrier layer; and
 - a second nonmagnetic electrode layer joined to the other end surface of said first ferromagnetic barrier layer.
3. The transistor according to claim 1 or 2, wherein said spin analyzer has comprises:
 - a second ferromagnetic barrier layer;
 - said second nonmagnetic electrode layer joined to one end surface of ~~the~~said second ferromagnetic barrier layer; and
 - a third nonmagnetic electrode layer joined to the other end surface of said second ferromagnetic barrier layer, ~~and shares~~wherein said second nonmagnetic electrode layer with this common to said spin injector and said spin analyzer.
4. The transistor according to claim 2 or 3, wherein said first and second ferromagnetic barrier layers ~~include~~comprise a ferromagnetic semiconductor or a ferromagnetic insulator.
5. The transistor according to any one of claims 1 to 4, wherein the thickness of said second nonmagnetic electrode layer is ~~below~~smaller than the mean free path of the spin-polarized hot carriers ~~of in~~ said second nonmagnetic electrode layer.
6. ~~The~~A transistor according to any one of claims 1 to 5, wherein ~~according to the spin - filter effect of said spin injector, in the tunnel effect of the carriers takes advantage of the fact that, in a carrier tunneling effect in said first ferromagnetic barrier layer which is produced by applying through the application of a voltage to said first nonmagnetic electrode layer and to said second nonmagnetic electrode layer, large is the tunnel probability those of the carriers having the that exist in said first nonmagnetic electrode layer and that have a spin direction of the spin-parallel to the a spin band at the band edge of said first ferromagnetic barrier layer of the carriers existing in said first nonmagnetic electrode layer, and small is the tunnel probability of the carriers having the direction of the spin anti-parallel thereto have a large tunneling probability, while those carriers with an antiparallel spin direction have a small tunneling probability.~~
7. The transistor according to any one of claims 1 to 6, wherein ~~according to the spin -filter~~

effect of said spin analyzer takes advantage of the fact that, when the spin direction of the ~~spin-of-spin-~~polarized hot carriers injected from said spin injector is parallel to the ~~direction of the spin~~that of the spin band at the band edge of said second ferromagnetic barrier layer, said spin-polarized hot carriers are ~~conducted~~transported through the spin band at the band edge of said second ferromagnetic barrier layer ~~to and~~ reach said third nonmagnetic electrode layer, ~~and whereas~~ when the spin direction of the ~~spin-of~~ said spin-polarized hot carriers is ~~anti-parallel to the direction of the spin~~antiparallel to that of the spin band at the band edge of said second ferromagnetic barrier layer, said spin-polarized hot carriers ~~cannot~~are unable to reach said third nonmagnetic electrode layer.

8. The transistor according to any one of claims 1 to 7, wherein a first voltage is applied by ~~a first power source between said first nonmagnetic electrode layer and said second nonmagnetic electrode layer, from a first power supply, and a second voltage is applied by a second power source between said second nonmagnetic electrode layer and said third nonmagnetic electrode layer or between said first nonmagnetic electrode layer and said third nonmagnetic electrode layer, and according to the relative directions of magnetization of said first ferromagnetic barrier layer and said second ferromagnetic barrier layer, spin-~~from a second power supply, and wherein said spin-polarized hot carriers injected from said first nonmagnetic electrode layer into said second nonmagnetic electrode layer are switched to either an electric current flowing viathrough said second ferromagnetic barrier layer and said second power source supply or an electric current flowing viathrough said second nonmagnetic electrode layer and said first power source, supply depending on the relative magnetization configuration of said first ferromagnetic barrier layer and said second ferromagnetic barrier layer.

9. The transistor according to claim 8, wherein said first voltage is applied ~~so~~such that the energy of the injected spin-polarized hot carriers ~~is~~becomes larger than the energy of the spin band edge ~~of energy at the band edge of the~~ said second ferromagnetic barrier layer and ~~is smaller than the energy in of the spin band edge to which the spin -split width is added to the energy of the spin band edge.~~

10. The transistor according to claim 9, wherein ~~a magnetic field is applied to invert any one of the directions of the relative magnetization of configuration in~~ said first ferromagnetic barrier layer ~~and/or~~ said second ferromagnetic barrier layer can be reversed with the application of a magnetic field.

11. A memory circuit ~~wherein comprising a memory cell formed by the transistor according to any one of claims 1 to 10 is a memory cell.~~10.

12. The memory circuit according to claim 11, wherein ~~the~~said second nonmagnetic electrode layer of said transistor is connected to a ~~word line, the~~wordline, ~~said~~ third nonmagnetic electrode layer of said transistor is connected to a ~~bit line~~bitline, said ~~bit line~~bitline is connected ~~via a load~~ to a power source supply via a load, and ~~the~~said first nonmagnetic electrode layer of said transistor is ~~grounded~~connected to ground.

13. A storage device memory element comprising:

a transistor (hereinafter, called a "spin transistor") including ferromagnetic substances containing a ferromagnet and having an output characteristic depending on the spin direction of the spin of carriers (to be hereafter referred to as a "spin transistor");

an information rewriting means ~~rewriting information in~~ writing means for writing information within said spin transistor by changing the magnetization state configuration of said ~~ferromagnetic substances~~ ferromagnet; and

an information reading sensing means ~~reading for sensing from~~ sensing from said output characteristics information stored in said spin transistor as ~~the~~ in terms of a magnetization state ~~from said output characteristic~~ configuration.

14. The storage device memory element according to claim 13, wherein said spin transistor has ~~at least one ferromagnetic substance (hereinafter, called a "free layer") capable of independently controlling the direction of magnetization and at least one ferromagnetic substance (hereinafter, called a "pin layer") not changing the direction of magnetization, and holds any one of two stored states of~~ comprises at least one ferromagnet in which the relative magnetization configuration can be independently controlled (to be hereafter referred to as a "free layer"), and a ferromagnet in which the relative magnetization configuration is not changed (to be hereafter referred to as a "pin layer"), wherein

one of two memory states, namely, a first state in which said free layer and said pin layer have the same direction of relative magnetization configuration, and a second state having in which they have different directions of magnetization configurations, is retained.

15. A storage device memory element according to claim 14, wherein ~~one a single spin transistor according to claim 14 is used to store~~ stores information according to in terms of the relative directions of magnetization of configuration of said free layer relative to said pin layer, and said free layer for detecting the wherein information stored in said transistor ~~based on an~~ is detected using the output characteristics of said spin transistor ~~depending, which depend on the relative directions of magnetization configuration of said pin layer and said free layer.~~

16. The storage device memory element according to claim 14 or 15, wherein said spin transistor ~~has~~ comprises: a first electrode structure for injecting spin-polarized carriers;

a second electrode structure for receiving said spin-polarized carriers; and

a third electrode structure for controlling the quantity amount of the spin-polarized carriers ~~conducted~~ transported from said first electrode structure to said second electrode structure, and ~~wherein~~

said pin layer and said free layer are included in any ~~one~~ of said first to third electrode structures.

17. A storage device memory element comprising:

~~one a single spin transistor according to described in claim 16;~~
a first ~~wire-grounding~~line connecting said first electrode structure to ground;

a second wireline connected to said second electrode structure; and
a third wireline connected to said third electrode structure.

18. A storage device memory element comprising:

~~one a single spin transistor according to claim 16;~~

a first ~~wire-grounding~~line connecting said first electrode structure to ground;

~~— a second wire connected to said second electrode structure;~~

~~— a third wire connected to said third electrode structure;~~

a second line connected to said second electrode structure;

a third line connected to said third electrode structure;

an output terminal formed at one end of said second wireline; and

a fourth wireline branching from said second wire to be line and connected via a load to a power source supply via a load.

19. The storage device memory element according to claim 17 or 18, further comprising a first ~~another wire~~separate line and a second separate line that intersect one another wire crossing on~~above~~ said spin transistor ~~to be~~in an electrically insulated ~~from each other~~manner.

20. The storage device memory element according to claim 19, wherein ~~in place of said first another wire and said second another wire or any one of said first another wire and said second another wire, said second wire and said third wire are used or any one of said second wire~~separate line and/or said second separate line are replaced with said second line and/or said third wire is usedline.

21. The storage device memory element according to claim 19 or 20, wherein information is written by reversing the magnetization of said free layer by a magnetic field induced by flowing electric currents to causing a current to flow through said first ~~another wire~~separate line and said second ~~another wire~~separate line, or through said second wireline and said third ~~wire~~ inverts the magnetization of said free layer to changeline, thereby changing the relative magnetization state ~~of~~configuration between said pin layer and said free layer ~~for rewriting information~~.

22. The storage device memory element according to claim 17 or 18, wherein information is ~~read based on an~~sensed using the output characteristics of said spin transistor when ~~applying a first bias~~is applied to said third wireline and a second bias is applied between said first wireline and said second wireline.

23. The storage device memory element according to any one of claims 18 to 22, wherein ~~when applying a first bias to said third wire, information is read by~~sensed using an output voltage that is obtained based on the basis of a voltage drop of across said load ~~produced due~~

to a current through said load and said spin transistor between said power source supply and said first wire and said load by an electric current via said spin transistor line when a first bias is applied to said third line.

24. A memory circuit comprising:

- ~~one~~ a single spin transistor according to claim 16 arrayned in a matrix;
 - ~~a first wire grounding line connecting each of said first electrode structures~~ structure to ground;
 - ~~a plurality of word lines sharably~~ wordlines commonly connecting said third electrode structures of said spin transistors arrayned in the column direction; and
 - ~~a plurality of bit lines sharably~~ bitlines commonly connecting said second electrode structures of said spin transistors arrayned in the row direction.

25. A memory circuit comprising:

- ~~the~~ spin transistor according to claim 16 arrayned in a matrix;
 - ~~a first wire grounding line connecting each of said first electrode structures~~ structure to ground;
 - ~~a plurality of word lines sharably~~ wordlines commonly connecting said third electrode structures of said spin transistors arrayned in the column direction;
 - ~~a plurality of bit lines sharably~~ bitlines commonly connecting said second electrode structures of said spin transistors arrayned in the row direction;
 - ~~an output terminal formed at one end of said bit line~~ bitlines; and
 - ~~a second wire line branching from said bit line to be~~ bitline and connected via a load to a power source supply via a load.

26. The memory circuit according to claim 24 or 25, further comprising a first ~~another wire~~ separate line and a second separate line that intersect one another wire crossing ~~on~~ above said transistor ~~to be in an electrically insulated from each other manner.~~

27. The memory circuit according to claim 26, wherein ~~in place of said first another wire~~ separate line and/or said second ~~another wire or any one of said first another wire and said second another wire,~~ said word line and said bit line are used or any one of said word line ~~separate line are replaced with said wordline and/or said bit line is used~~ bitline.

28. The memory circuit according to claim 26 or 27, wherein ~~a magnetic field induced by flowing electric currents to said first another wire and said second another wire or said word line and said bit line inverts~~ information is written by reversing the magnetization of said free layer to change by a magnetic field induced by causing a current to flow through said wordline and said bitline, thereby changing the relative magnetization state of said free layer and configuration between said pin layer for rewriting information and said free layer.

29. The memory ~~circuit~~ element according to claim 24 or 25, wherein information is read ~~based on a sensed using the output characteristics of said spin transistor when applying a first bias is applied to said word line~~ wordline and a second bias is applied between said first

~~wireline~~ and said ~~bit line~~. bitline.

30. The memory ~~circuit~~element according to any one of claims 25 to 27, wherein ~~when applying a first bias to said word line, information is read by~~sensed using an output voltage that is obtained based on the basis of a voltage drop of said load produced across said load due to a current through said load and said spin transistor between said power source supply and said first wire and said load by an electric current via said spin transistor~~line when a first bias is applied to said third line.~~

31. A storage device ~~memory element~~ comprising:

a first and a second spin transistors according to claim 16;

~~a first wire grounding line connecting the first electrode structure shared between, which is common to said first and said second spin transistors, to ground;~~

a second and a third wires connecting line connected to the second electrode structure of said first spin transistor and the second electrode structure of said second spin transistor, respectively; and

a fourth wire connecting line connected to the third electrode structure of said first spin transistor and the third electrode structure of said second spin transistor.

32. A memory circuit comprising:

a plurality of spin transistors according to claim 16 ~~arrayed in a matrix;~~

~~— a first wire sharing and grounding said a first line commonly connecting to ground the first electrode structures of a plurality of spin transistors arranged in a first row and the first electrode structures, of said plurality of spin transistors, in the row of a plurality of first spin transistors arrayed in the row direction and in the row of a plurality of second spin transistors arrayed in the row direction adjacent to the row of said first spin transistors in the column direction; of a plurality of spin transistors arranged in an adjacent, second row;~~

~~— a first bit line sharably connecting said second electrode structures, of said plurality of spin transistors, in the row of a plurality of first spin transistors arrayed in the row direction, and a second bit line sharably connecting said second electrode structures in the row of second spin transistors adjacent to the row of said first spin transistors in the column direction; and~~

a first bitline commonly connecting the second electrode structures of a plurality of spin transistors arranged in a first row and the second electrode structures of a plurality of spin transistors arranged in a second row adjacent to said first row in the column direction;

a second bitline commonly connecting the second electrode structures of said spin transistor in said first row and the second electrode structures of said second spin transistors in said second row adjacent to said first row in the column direction; and

~~a word line sharably~~a wordline commonly connecting the third electrode structures, of said plurality of spin transistors, in the column of a plurality of spin transistors arrayed in the in a column direction.

33. A memory circuit comprising:

a plurality of spin transistors according to claim 16 arrayed in a matrix;
~~— a plurality of first wires sharing and grounding said first electrode structures, of said plurality of spin transistors, in the row of a plurality of first spin transistors arrayed in the row direction and in the row of a plurality of second spin transistors arrayed in the row direction adjacent to the row of said first spin transistors in the column direction, one first wire being provided every two rows;~~

~~— a plurality of first bit lines sharably connecting said second electrode structures, of said plurality of spin transistors, in the row of a plurality of first spin transistors arrayed in the row direction, one first bit line being provided every two rows of said spin transistors, and a plurality of second bit lines sharably connecting said second electrode structures in the row of second spin transistors adjacent to the row of said first spin transistors in the column direction, one second bit line being provided every two rows of said spin transistors; and~~

a plurality of first lines each commonly connecting to ground said first electrode structures of a plurality of spin transistors in a first row and those of a plurality of spin transistors in a second row adjacent to said first row in the column direction, wherein each of said first lines is provided for every two rows;

a plurality of first bitlines each commonly connecting said second electrode structures of a plurality of said spin transistors arranged in a first row, wherein each of said first bitlines is provided for every two rows;

a plurality of second bitlines each commonly connecting the second electrode structures of a plurality of spin transistors arranged in a second row adjacent said first row in the column direction, wherein one such second bitline is provided for every two rows of said spin transistors; and

a plurality of word lines sharablywordlines commonly connecting the third electrode structures, of said plurality of spin transistors, in the column of a plurality of said spin transistors arrayed in the column direction.

34. The ~~storage device~~memory element according to claim 20, wherein information is written by reversing the magnetization in said free layer by a magnetic field induced by flowing electric currents to causing a current to flow through said second wireline or said third wireline with which any one of said first another wire and separate line or said second another wire is separate line have been replaced and, or through said first another wire or said second another wire which is not replaced with these inverts the magnetization of said free layer to change separate line or said second separate line that has not been replaced thereby, thus changing the relative magnetization state of configuration between said pin layer and said free layer for rewriting information.

35. The memory circuit according to claim 27, wherein information is written by causing the relative magnetization configuration between said free layer and said pin layer to be changed by a magnetic field induced by flowing electric currents to said word linecausing a current to flow through said wordline or said bit linebitline with which any one of said first another wire and separate line or said second another wire is replaced and separate line have been replaced, or through said first another wire or said second another wire which is not

~~replaced with these changes the relative magnetization state of said free layer and said pin layer for rewriting information~~separate line or said second separate line that has not been replaced thereby.

ABSTRACT

~~There are provided a~~ A spin transistor ~~having~~ comprises a spin injector for injecting, as hot carriers, carriers having from a first nonmagnetic electrode carriers with a spin parallel to the spin band ~~constituting~~ forming the band edge of a first ferromagnetic barrier layer ~~from a first nonmagnetic electrode into,~~ to a second nonmagnetic electrode layer and, as hot carriers. It also comprises a spin analyzer conducting, by the whereby, due to spin -splitting at the band edge of a second ferromagnetic barrier layer, the ~~hot carriers~~ spin-polarized hot carriers are transported to a third nonmagnetic electrode when the direction of the spin of the ~~spin-polarized hot carriers injected into the second nonmagnetic electrode is parallel to the direction that~~ of the spin of the spin band at the band edge of the second ferromagnetic barrier layer ~~and not conducting the hot carriers, whereas the hot carriers are not transported to the third nonmagnetic electrode when they are anti parallel, and a storage device using the~~ in the case of antiparallel spin. A memory element is also provided that comprises such a spin transistor.